Sedimentology, stratigraphy and palaeogeography of Oligocene to Miocene rocks of North Canterbury-Marlborough

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Abstract

The Cenozoic was a time of climatic, tectonic and eustatic change in the Southern Hemisphere. Cooling at the pole, glaciation and substantial sea ice formation occurred as latitudinal temperature gradients increased and tectonics altered Southern Hemisphere circulation patterns. During this same time frame, the tectonic regime of the New Zealand continental block transitioned from a passive margin to an active plate boundary, resulting in the reversal of a long-standing transgression and an influx of terrigenous sediment to marine basins. In this transition, depositional basins in the South Island became more localized; however, the influence of oceanographic and tectonic drivers is poorly understood on a local scale. Here we apply sedimentological, biostratigraphic and geochemical analyses to revise understanding of the effects of the changing climatic regime and active tectonics on the development of Oligocene and Miocene rocks in the Northern Canterbury Basin.

The Late Oligocene to Middle Miocene sedimentary rocks of the northern Canterbury Basin record oceanographic and tectonic influences on basin formation, sediment supply and deposition. The Palaeocene to Late Eocene Amuri Formation in the basin are micrites and biogenic cherts recording deepwater, terrigenous-starved environments, and do not show any influence of active tectonics. The Early Oligocene development of ice on the Antarctic continent and the associated global sea level response is reflected in this basin as the Marshall Paraconformity, an eroded, glauconitized and phosphatised firm ground and hardground atop the Amuri. Sedimentation above this unconformity resumed in the Late Oligocene-Early Miocene with cleaner, deep-water, bathyal planktic foraminifera packstones and wackestones in eastern areas and Late Oligocene inner shelf volcaniclastic packstones in parts of the western basin. Post-unconformity sedimentation resumed earlier in western areas, as the currents responsible for scouring the sea floor moved progressively to the east. The development of tectonic uplift in terrestrial settings is first seen in the northwestern basin in

Lower Miocene fine quartz-rich sandstones, and by the Middle Miocene, bathyal sandstones and quartz-rich wackestones appear in the basin, replacing earlier, more pure carbonates. The uplift caused shallowing to the west, in the form of shelf progradation due to sediment influx. This shallowing is not observed to the east; instead, the palaeoenvironments show a deepening as a result of sea level rise.

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1 INTRODUCTION

1.1 Introduction

The focus of this thesis is on the Late Oligocene to Mid Miocene sedimentary rocks of the northern Canterbury Basin, located on the south-eastern margin of New Zealand. During the Oligocene and Miocene, Southern Hemisphere oceanography was undergoing a major reorganization as a result of Antarctic glaciation and changing, cooling temperatures and the tectonic separation of Antarctica, Australia and South America (Fulthorpe et al., 1996; Lu et al., 2005). During this same time frame, the tectonic regime of the New Zealand continental block transitioned from a passive margin to an active plate boundary, resulting in the reversal of a long-standing transgression and an influx of terrigenous sediment to marine basins (Carter, 1988). These rocks, and their associated unconformities, record the effect of oceanographic and tectonic change on sediment supply, deposition and basin formation. It is the goal of this project to determine the detailed palaeogeographic development of the North Canterbury Basin and to discern between tectonic and oceanographic drivers of this development. This will be achieved by the interpretation of sedimentological, palaeontological and isotope stratigraphy data from the Kaikoura-Waiau to Gore Bay region.

1.2 New Zealand Geological History and Southern Hemisphere Oceanography

The development of modern Southern Hemisphere geography began in the Cretaceous, beginning with the separation of New Zealand from Gondwana at 80Ma which resulted in isolation of Zealandia from Australia via the Tasman Sea. New Zealand's geology became distinct from that of neighbouring continents, but remained influenced by the same global climate events and trends as the other landmasses. Following a global warming period through the Palaeocene-Eocene, the final tectonic separation of Antarctica and Australia at 38Ma initiated changes in oceanic circulation patterns which in turn altered the regional climate (Kennett, 1977). These changes began at the Eocene-Oligocene boundary (34Ma), with a cooling period termed the "Eocene Terminal Event". During this time, water temperatures dropped ~5°C, ice sheets formed on East Antarctica and thermohaline circulation much like that of present day was initiated (Shackleton and Kennett, 1975). The climatic change was rapid, with much of the ice expansion occurring in less than 50ky (Zachos and Kump, 2005). This shift was apparently brought on by a combination of declining atmospheric CO_2 concentration and, to a lesser extent, thermal isolation of Antarctica (DeConto and Pollard, 2003; Kennett, 1977). The concentration of CO_2 declined at a rate as high as ~56 p.p.m.v. per million years and was most likely initiated by increased silicate weathering as a result of the Himalayan orogeny (Zachos and Kump, 2005). Eocene-Oligocene global cooling is evidenced by changes observed in benthic and planktic foraminifera. Both planktic and shallow water benthic faunas from this time underwent major characteristic changes, while deep sea benthic foraminifera underwent a major crisis (Kennett, 1977). Foraminifera, in particular their response to environmental changes, are particularly useful to make interpretations of oceanographic conditions and changes. During this particular shift, biogenic activity increased due to the thermohaline circulation-induced upwelling of cold, nutrient-rich water (Kennett, 1980), resulting in the deposition of carbonate-rich Oligocene rocks (Van Andel et al., 1975). The increase in bottom water activity, associated with the changes in circulation, have also been attributed to causing widespread, deep-sea erosive unconformities at the Eocene-Oligocene boundary (Kennett, 1977; Fulthorpe et al., 1996). According to Kennett (1977), this was one of the most significant deep-sea erosive events of the Cenozoic.

At the same time as the Eocene Terminal Event, a transgression affected the New Zealand continental block, despite the global cooling trend. Thermal subsidence associated with the separation from Gondwana in the Cretaceous, coupled with crustal extension and erosion through the early Cenozoic, resulted in extremely low topographic relief by the Early Cenozoic (Cooper and Cooper, 1995). The low relief led to a nearly complete submersion of the continent in the Oligocene as the result of a widespread marine transgression, which reduced New Zealand to a chain of small islands (Cooper and Cooper, 1995; King, 2000). The maximum percentage of land submerged is contentious, but estimates are that 82-100% of the present-day landmass was underwater (Cooper and Cooper, 1995; Landis et al., 2008). The resulting geology of this transgression was widespread deposition of biogenic limestones and greensands on both the present-day continental plateau and offshore; the unit deposited at this time of particular interest to this project is the Amuri Limestone. Carter (1988) suggests the cause of the transgression to be epeirogenic thermal subsidence of the continental margin. Peak transgression in New Zealand occurred around 34 Ma, and was immediately followed by a lowstand (Fulthorpe et al., 1996). This sudden eustatic drop has been attributed to the climate shift and formation of Antarctic glaciers during the Eocene Terminal Event.

Oceanic circulation evolved further when the Tasman Gateway fully opened at 31Ma, at which point the Australian and Antarctica continents had completely separated (Fulthorpe et al., 1996; Nelson and Cooke, 2001). The opening of the Tasman Gateway allowed, for the first time, unimpeded flow of the proto-Antarctic Circumpolar Current (ACC). Warmer subtropical gyres became separated from the colder southern gyres, which led to the emplacement of thermal biogeographic barriers at high southern latitudes, affecting the distribution and migration of planktic organisms (Kennett, 1980). Development of the proto-ACC resulted in off-shoots of cool water which flowed northeast, directly affecting New Zealand sedimentation. The currents resulted in widespread erosion and unconformities through deep water carbonates (Nelson and Cooke, 2001). Fulthorpe et al. (1996) hypothesise that these off-shoots may have been the currents responsible for the formation of the Marshall Paraconformity. The ACC was fully developed in the Late Oligocene, once the Drake

Passage opened between South America and Australia (Carter et al., 1996). This had been the final barrier preventing full circumpolar flow. The Antarctic Circumpolar Current, now fully developed, resulted in a “major reorganization” of southeast Pacific and Southern Ocean sediment patterns (Kennett, 1977). This was the last major change in ocean currents and sedimentation; the basic patterns of both were in place by Early Neogene (Kennett, 1977). Increasingly warm conditions developed throughout the Pacific during the mid-Miocene, with temperatures peaking at 16Ma, during an event known as the Neogene Climatic Optimum. Immediately following this event, a long-term regression and global climate deterioration began. This led to an increased permanent ice accumulation on East Antarctica around 14Ma (McGowran et al., 1997) and a permanent ice sheet on the previously ice-free West Antarctica by late-Miocene (Hodell and Kennett, 1986; Nelson and Cooke, 2001). The substantial increase in ice, coupled with tectonically-induced widening of the Southern Ocean, expanded and increased the intensity of the ACC (Nelson and Cooke, 2001). Warm water currents which had surrounded New Zealand during the Climatic Optimum were replaced by colder waters, documented in the rock record as a shift from subtropical microfossil taxa to subantarctic assemblages (Nelson and Cooke, 2001). This series of events lead to the creation of a climate feedback loop, which resulted in a continued decrease of global temperatures, increased temperature gradients and an expansion of cold Antarctic surface water (Kennett, 1977)

In this background of global cooling was the inception of the proto-Alpine Fault system in New Zealand. This event, at the Eocene-Oligocene boundary, marked a shift from a passive margin to an active plate boundary (Norris et al., 1990). Initial movement along the fault was transcurrent, causing a north-trending tectonic lineament through the South Island due to crustal extension (King, 2000). This activity mainly affected only the western coast of the South Island however; the eastern South Island remained relatively tectonically stable through the late Eocene and possibly into the Oligocene, continuing to evolve as a passive margin (King, 2000). Transpressional movement and an increased component of strike-slip motion replaced the transcurrent regime along the Alpine Fault system at ~21Ma , reactivating former strike-slip faults as reverse or thrust faults (Lu et al., 2005). This event, which caused a major shift in long-standing sedimentation patterns, is marked in the rock record by an influx of terrigenous sediment. Terrigenous sedimentation began replacing carbonates across New Zealand as basement Torlesse and overlaying units were uplifted and eroded (King, 2000), resulting in the Oligocene carbonates being overlain by mid-Miocene bathyal siltstones and sandstones, such as the Waima Formation and the Great Marlborough Conglomerate debris-flow deposits (Browne, 1995). In the Canterbury region, compression resulted in upwarping and emergence of the shelf during the early Miocene (Field et al., 1989).

The Kaikoura Orogeny commenced in the late mid-Miocene, and was accompanied by relatively high sedimentation rates in the Canterbury Basin of > 22mm/yr from 15 – 11.5Ma (Lu et al., 2005). These sedimentation rates, however, are mostly attributed to global climate cooling and eustatic forcing, with tectonism playing only a secondary role (Lu et al., 2005). Not until 11.5Ma did tectonism become the dominant control of sedimentation in the Canterbury Basin (Lu et al., 2005). The Southern Alps are estimated to provide almost all eroded material in the South Island, and at least 20-30% of that material has been deposited in eastern basins, including the Canterbury Basin (Lu et al., 2005).

1.3 Regional Geology

The Oligocene in New Zealand is characterized by widespread carbonate deposition (Field et al., 1989). In the Canterbury region, deposition of the Amuri Limestone began in the upper Eocene and continued through to the mid Oligocene. This unit is a predominantly siliceous, micritic limestone, cherty limestone or interbedded limestone and marl, and was deposited under pelagic to hemipelagic conditions during a transgressive cycle when flooding over the continent was at its peak (Rattenbury et al., 2006). Early-mid Oligocene water depths, as indicated by foraminifera and the fine-grained character of the rock, suggests a palaeoenvironment of outer shelf to slope (Field et al., 1989). While alternative lithostratigraphy exists, the nomenclature of this project will follow Rattenbury (2006) (Fig. 1.1). In the field area covered by this project, the Amuri Limestone is classified as a member of the Muzzle Group; more southern occurrences have been assigned to the Eyre Group (Rattenbury et al., 2006).

The top of the Amuri, which is marked by the Marshall Paraconformity, is highly time-transgressive (Rattenbury et al., 2006). The time-transgressive nature of the unit is a direct result of the same forces which were responsible for the paraconformity, which represents a 2-4Ma break in sedimentation, from approximately 32-28 My. In some locations, such as such as Kaikoura, not only did the proto-ACC prevent the accumulation of sediment over the basin (Fulthorpe et al., 1996; Nelson and Cooke, 2001), it also appears to be responsible for erosion of poorly lithified Early Oligocene or even Late Eocene Amuri sediments (Rattenbury et al., 2006). As a result, the age of the top of the Amuri varies locally, younging progressively southwards from Kaikoura, where the top of the unit is Late Eocene (Rattenbury et al., 2006).

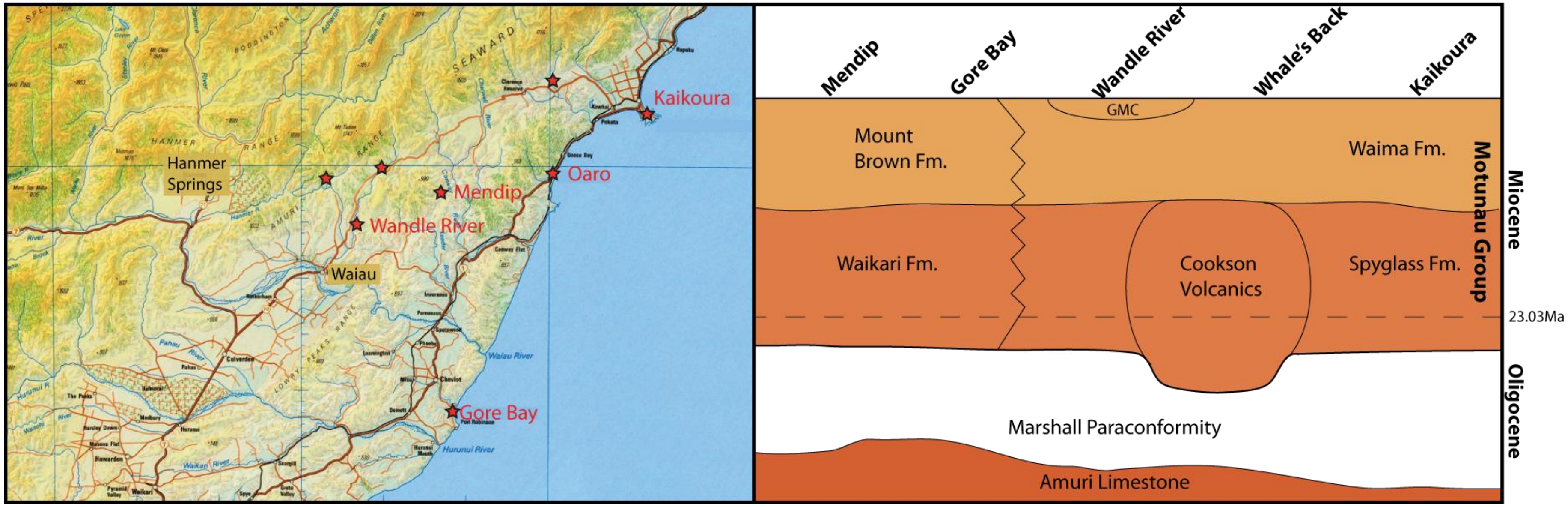


Figure 1.1 Map of field area (a) and generalized stratigraphy of area (b) (modified from Rattenbury et al., 2006**)**

The Marshall Paraconformity itself is a contentious issue, both in regards to its origin and name (Carter, 1985; Fulthorpe et al., 1996). The present-day consensus is that it is an unconformity (Fulthorpe et al., 1996), however the term “Marshall Paraconformity” is still commonly used. It will hereby be referred to as the Marshall Paraconformity, or “the unconformity”.

Unconformably overlaying the paraconformity is a thin limestone unit, the first unit of the Motunau Group. Combined into an undifferentiated group of Late Oligocene basal greensands and limestones by Rattenbury (2006), the unit includes the Spyglass and Weka Pass formations. These formations are variably shallow to deep water limestones that are essentially a continuation of carbonate sedimentation in the absence of terrigenous supply (Rattenbury et al., 2006). Often occurring at the base of the unit are a few scattered phosphate nodules or inclusions incorporated from the underlying Paraconformity. In western areas of the Kaikoura mapsheet, the limestone is locally interbedded with the Cookson Volcanic Group (Rattenbury et al., 2006). The Spyglass Fm, outcropping at Kaikoura, is a stylobedded packstone with a maximum thickness of ~50m (Browne, 1995). The formation varies geographically though; while the northern outcrops around Kaikoura are deep water, highly glauconitic interbedded packstone, the Gore Bay outcrop to the south is an outer shelf-upper slope wackestone.

Conformably overlying the limestones in the east is the Early- Mid Miocene Waima Fm, a massive, calcareous, blue-grey, fine- to medium- grained bioturbated siltstone (Browne, 1995), which is up to 360m thick (Rattenbury et al., 2006). Foraminifera indicate outer shelf to bathyal settings, with depths reaching 1500m (Browne, 1995). Within the unit are well-indurated horizons with occasional concretions (Browne, 1995). Also interbedded with the siltstone are centimetre to decimetre thick sandstones, often with sharp contacts above and below (Browne, 1995). In the northern portion of the field area the Great Marlborough

Conglomerate (GMC) occurs as lenses within the Waima Fm. This conglomerate was deposited by various debris flow mechanisms into shallow channels or canyons incised into the continental shelf (Rattenbury et al., 2006).

The southern equivalent of the Waima is the Mt Brown Fm. Within this field area, it was observed in only one locality, at what may be its northern-most extent, in the Mendip region (Fig. 1.1). The formation consists of siltstone, sandstone and bioclastic limestone, and was deposited in a mid-outer shelf environment in the subsiding basin (Rattenbury et al., 2006).

1.4 Research Questions and Aims

While both the Cenozoic history of Southern Hemisphere processes and the various geologic formations of the Canterbury Basin are well known, the detailed palaeogeographic development of localised basins has yet to be fully explored. The main research aims of this project are:

1. To resolve the detailed palaeogeography of the North Canterbury Basin through the Oligocene – Miocene.
2. Determine the role of global oceanography and local tectonics on palaeogeographic development of North Canterbury.
3. Determine if the influence of global climate and local tectonics be distinguished from each other.

This will be achieved by the study of microfossil data (specifically foraminifera) and sedimentological details, as described in the following methods section.

2 STRATIGRAPHY AND SEDIMENTOLOGY

2.1 Introduction

This chapter presents the sedimentology and stratigraphy of the field area, reviews point counting data, segregates the data into lithofacies and presents the stratigraphic columns constructed from data collected while in the field.

The seven different lithofacies encountered in the field area, described in section 2.4, were determined from observations in the field, petrography and point counting. The palaeoenvironments and palaeogeography of the lithofacies are discussed in Chapter 5.1 and 5.2, respectively.

2.2 Methods

Field Work

Field work was conducted over a two week period in October 2010, with some additional visits to the area throughout 2011. The region covered was the northern portion of the Canterbury Basin, from Gore Bay to the Kaikoura-Waiau area (Fig. 2.1). The purpose of the field work was to measure stratigraphic sections of Oligocene-Miocene successions and to collect samples for biostratigraphic, petrographic and geochemical analysis.

Sections were selected based on the presence of good Oligocene-Miocene outcrop. Many of the sections were selected before going out to the field, having been known outcrop localities, while a few were discovered while in the field. At each outcrop, a section was measured if possible; the locations with measured sections are Gore Bay, Oaro, Kaikoura (Point Keen and South Bay), Little Lottery River, Whale's Back area, Wandle River, Mendip and Cribb Creek.

Samples for foraminifera and petrography were taken at intervals throughout the section, at points such as a lithological change or prominent feature. Collecting tools (rock hammer) and bags were clean to avoid contamination, and samples excluded weather surfaces.

In total, 59 hand samples were collected, 13 of which yielded enough foraminifera for biostratigraphic work and 25 were selected for petrographic work. A further 55 samples were collected to be used exclusively for geochemical work, which is described in Chapter 4. All samples are detailed in Appendix A.

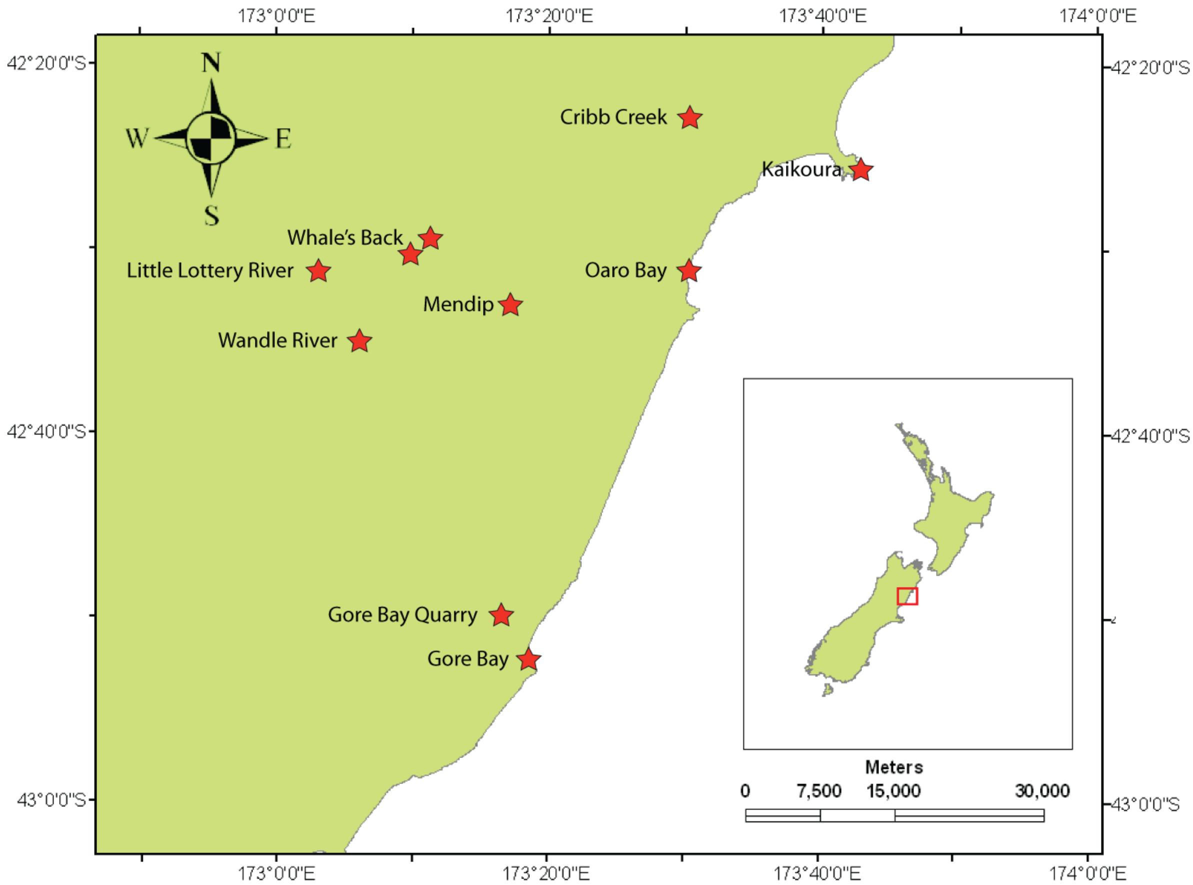


Figure 2.1 Map of study location. Stars mark locations of measured sections.

Thin section analysis and point counting

A total of 18 thin sections were analyzed for percentage of glauconite, carbonate and siliciclastics, as well as for a planktic-to-benthic ratio of foraminifera specimens. This was done in one of two ways- where grain size was fine sand or coarser, a point counter was used, and where the grain size was too fine to use the point counter, the percentages were estimated. A Pelcon Point Counter was used for 10 samples, set up with a step length ranging from

0.07mm to 0.1mm, depending on the grain size of the sample, and an average of 400 counted points to ensure accurate percentages. All raw data can be viewed in Appendix A.

2.3 Facies description and stratigraphy

2.3.1 Stratigraphic Overview

As discussed in the Section 1.3, Regional Geology, the stratigraphy of this project covers the Amuri Limestone, Marshall Paraconformity, and the two formations of the Motunau Group. The formations has a variety of characteristics across the field area, which are summarized here.

Amuri Limestone

Only the uppermost portion of this Formation was observed for the project. The top of the Amuri is a very pure micritic limestone, with *Thalassinoides* burrows extending to a maximum of 1.5m down from the top, which are infilled with both micrite and glauconite-rich sandstone.

Marshall Paraconformity

The so-called Marshall Paraconformity is observed at all the locations in the field where the transition from Amuri Formation to Motunau Group is visible. The sharp erosional surface of the Marshall Paraconformity is consistently overlain by a distinctive lag deposit, composed of phosphatised Amuri Limestone clasts and glauconitic sandstone, which constitutes the base of the Motunau Group.

Lower Motunau Group

The unit directly overlying the Paraconformity ranges in both rock type and thickness across the field area; it is made up of limestones, volcaniclastic sandstones and calcareous sandstones, ~11-60m thick. Typically at the base of the Motunau Group occurs the previously mentioned 10-20cm thick horizon of phosphatised Amuri Limestone clasts, ranging in size from medium to very coarse pebble, in a glauconitic sandstone matrix which is highly bioturbated by *Thalassinoides.* A sharp break separates the top of this horizon from the remainder of the unit above. These units are the Spyglass Formation and the correlative limestones at Cribb Creek, Oaro and Gore Bay, which are foraminifera-rich and lacking in many sedimentary structures or macro fossils. The Cookson Volcanics, unique in the area as it is only observed at Whale's Back, is a fossil-rich unit composed entirely of coarse basalt clasts, glauconite and carbonates. The third rock type observed in the lower Motunau Group is a fine grained calcareous sandstone at Mendip Hills, which is devoid of fossils or sedimentary features.

Upper Motunau Group

The upper Motunau Group, including the Waima and Mt Brown Formations, differ from the lower Motunau Group primarily by the high siliciclastic content. Most of the outcrops observed are highly calcareous sandstones, though some of the eastern sites, while experiencing an increase in siliciclastics, retained enough carbonate to still be classified as limestones. The siliciclastic content of these rocks is dominated by quartz, with minor feldspar and mica constituents. Also included in the upper Motunau Group is the Great Marlborough Conglomerate, which was observed at Little Lottery River. It was inaccessible and therefore not analysed or described here.

2.3.2 Lithofacies descriptions

Throughout the field area, seven distinct lithofacies were identified: 1) Volcaniclastic Calcareous Sandstone, 2) Foraminiferal Wackestone, 3) Foraminifera Packstone , 4) Muddy Quartz Sandstone, 5) Fossiliferous Sandstone, 6) Impure Wackestone and 7) Calcareous Fine Sandstone. A detailed description of each lithofacies follows.

Volcaniclastic calcareous sandstone

Figure 2.2 Outcrop at Whale's Back (a) and thin section photograph from sample JI49 (b)

Overview

Occurrence: Whale's Back region 42°29'29"S 173°11'18"E

Carbonates: 33% Siliciclastics: 62%

Glauconite: 5% Planktic/benthic forams: 3:97

This volcaniclastic sandstone lithofacies is predominantly composed of red, poorly-sorted, medium-coarse sand basalt fragments and varying quantities of unidentifiable calcite fragments (0-10%) and angular cobbles (0-30%). Fossil fragments and macrofossils including bivalves, gastropods and echinoderm spines, are common. This lithofacies, while generally massive and lacking internal structures, does contain large scale (5-10m) beds with sharp contacts which most likely represent various pulses of activity from a nearby volcano. While most of these beds are composed of medium-coarse sand basalt fragments, one in particular is devoid of fossils and is made up of ~30% angular cobbles.

Analysis, via point counting, was done on sample JI49, a poorly-sorted medium sandstone. It showed that the lithofacies is made up of 62% lithics, 5% non-carbonates (glauconite) and 33% carbonate. The lithics were entirely autochthonous, composed entirely of basalt clasts. The sample contains no allochthonous clasts such as quartz. Fossils, including glauconitized benthic forams, make up 2% of the sample. The remaining 31% of the sample is spar cement.

One of the measured beds was unique within the lithofacies. This 4.5m thick bed occurred 25m up the section and was especially fossiliferous, with bivalves, gastropods and echinoderm spines measuring up to 5cm in size (Fig. 2.3). While there was no visible grading of the clasts in the bed, this most likely represents reworking of the volcanics, therefore incorporating the shells in with the volcanic clasts.

In total, five samples were collected from the lithofacies. Three were sieved, but only one (JI49) yielded foraminifera (the results of which will be discussed in the following chapter). A further three had thin sections cut, of which one (JI49) was useful for analysis.

Figure 2.3 Fossils in the Whale's Back volcaniclastic sandstone. a) locally abundant bivalves b) small epifaunal bivalve (pectenid) c) gastropod d) calcareous worm tube

Foraminiferal Wackestone

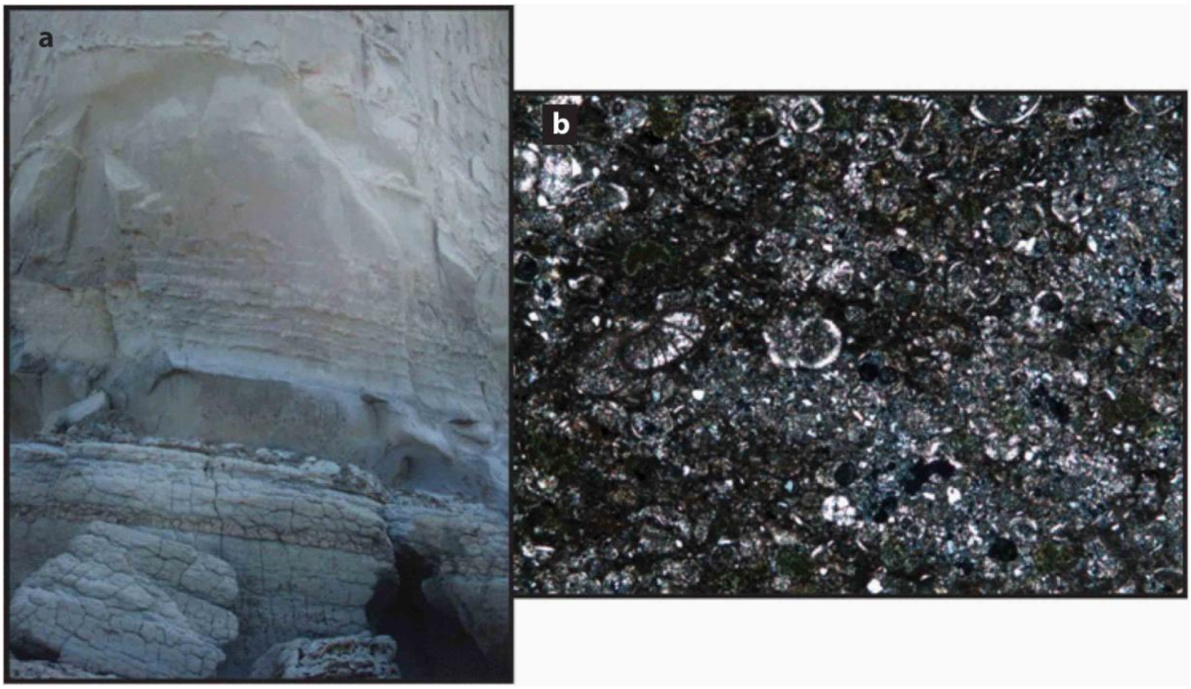


Figure 2.4 Picture of Gore Bay outcrop immediately above the Marshall Paraconformity (a) and representative thin section from sample JI1 (b)

Overview

Locations: Gore Bay 42°52’16”S, 173°3’E; Gore Bay Quarry 42°49’50”S, 173°16’36”E,

Cribb Creek 42°22’53”S, 173°30’17”E

Carbonate: 75-90% Siliciclastics: 10-25%

Glauconite: 5-15% Planktic/benthic forams: 7:3 – 9:1

This lithofacies, a foraminiferal wackestone, was observed at Gore Bay, Gore Bay Quarry and Cribb Creek. It generally consists of a bedded-to-massive, occasionally bioturbated fine wackestone, with uncommon sedimentary features (parallel laminations) throughout the section and rare fossil fragments.

At Cribb Creek, a combination of diagenetic alteration and recent landslips has removed any trace of any sedimentary features which rendered detailed field observations impossible. Likewise, the Gore Bay quarry site was inaccessible after the first 2m above the unconformity. However, with thin section analysis, it was possible to correlate these three sites. At, Cribb Creek thin section analysis of sample JI34 was done via point counter, while the three other samples from Cribb Creek were estimated visually. Carbonate content gradually decreases through the section, beginning at 75% and decreasing to 65%. The decrease in carbonate content is due to an increase in glauconite, not due to an increase in siliciclastics (see Fig. 5.2). The carbonate percentage is much higher further south, with Gore Bay Quarry at 82% and Gore Bay at 85-90% . At Gore Bay, the carbonate fraction is micrite (44%), spar (1%) and bioclasts (36%); at Cribb Creek, spar makes up most of the matrix (52%) with some micrite in the sample as well (11%). Bioclasts (11%) and calcite crystals (1%) make up the rest of the carbonate fraction. The bioclasts observed were almost entirely planktic forams; 70% planktics at Gore Bay, 82% at Gore Bay Quarry and 91% at Cribb Creek. The other bioclasts included include trace amounts of echinoderm and bryozoan fragments.

Siliciclastics, almost entirely quartz, are angular to sub-rounded, and these clasts are moderately well sorted. Siliciclastics make up 3-7% of the sample at Gore Bay, 7% at Gore Bay Quarry and ~20% through Cribb Creek.

Glauconite content at Gore Bay, when analyzed by point counting, is ~8% through the section. In outcrop however, it appeared much higher, with estimates ranging from 20-30% throughout. Where the point counting data was present, those results were taken as accurate over the hand sample estimates. At Cribb Creek, the glauconite content alternates between 5% and 15%. At the base of the Gore Bay Quarry section, glauconite content is 11%.

There is one notable exception to the otherwise repetitive succession of wackestone at the Gore Bay location, which a turbidite sequence occurs 6m above the base of the Motunau Group. This turbidite is recognized as a 60cm bed of normally graded bed of non-calcareous quartz sandstone with an erosive base. At the base of the bed is a horizon of sub-angular Amuri pebbles and cobbles, which then grades in to a bedded quartz sandstone. The top of the bed is well laminated, contains load casts and is highly bioturbated by *Ophiomorpha*.

In total, 2 samples were taken at Gore Bay, 1 from Gore Bay Quarry and 4 from Cribb Creek for the purpose of thin sections and foraminifera extraction. The Gore Bay thin sections analyzed were JI1 and JI2, collected immediately above the unconformity and 7m above, respectively. Both contained forams. At Gore Bay Quarry, one sample (JI28) was collected 1m above the unconformity, and was used for thin section analysis via point counting as well as foraminifera analysis. The Cribb Creek thin sections collected and analyzed were JI34, CC+9, CC+ 20, CC+30, which were collected 5m, 9m, 20m and 30m above the unconformity, respectively. The three CC samples were additional thin sections made for geochemical analysis (discussed in Chapter 4), but were also used to augment carbonate to silicate ratio analysis throughout Cribb Creek sections. No samples from Cribb Creek yielded forams.

Foraminifera Packstone

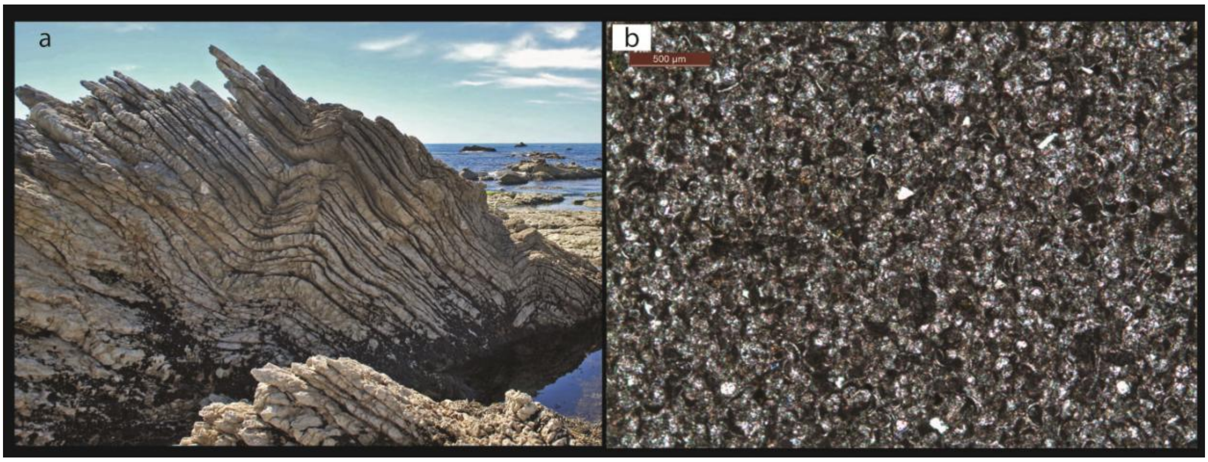


Figure 2.5 Picture of a Kaikoura outcrop of the Foraminifera Packstone at the top of the Spyglass Fm. (a) and representative thin section from sample JI14 (b)

<u>Overview</u>

Locations: Kaikoura South Bay 42°25’33”S 173°41’33”E; Kaikoura Point Keen 42°24’52”S 173°42’19”E; Oaro 42°30’58”S 173°30’27”E

Carbonate: 85-95% Siliciclastics: 1-5%

Glauconite: 4-10% Planktic/benthic forams: 9:1 – 1:0

This lithofacies, observed at Kaikoura and Oaro, is a glauconitic, muddy, foraminifera packstone with a high concentration of planktic foraminifera and is essentially devoid of siliciclastics. Characteristic of this lithofacies is fine interbeds of glauconitic calcarenite within the packstone. The main differences between this lithofacies and the last is the absolute lack of siliciclastics in this sample, compared to the 10-25% found in the Foraminifera Wackestone, as well as the higher percentage of mud in the Foraminifera Packstone.

Thin sections were taken for analysis throughout the section (Fig. 2.16,17). In both Oaro and Kaikoura, the lower 2-3 metres contained less foraminifera and more mud than the upper portions, making it a wackestone, though the units rapidly grade into packstone. The samples are well sorted, and the glauconite grains rounded to well-rounded. Glauconite is the dominant, and sometimes only, non-carbonate component of the samples; quartz grains remained a constant 1% of the sample at Kaikoura, and never increased past 3% at Oaro, whereas glauconite is always present and makes up 5-10% of the sample. Micrite, the dominant matrix, constitutes 30-60% of each sample (the lower wackestone samples contain 40+% of micrite, while the packstone samples contain 30-40%). Foraminifera and other bioclasts make up 30% of the samples at Oaro, and 50-65% at Kaikoura, peaking in sample 12 (10m above the Paraconformity). The foraminifera assemblages are dominated by planktics; at Oaro, the percent planktics varies between 65-95%, and at Kaikoura it varies between 90-100%. See Figure 5.2 for a visual representation.

The glauconite-rich sandstone layers at Kaikoura are identical to the other layers in terms of percent quartz, planktic foraminifera and cement, except the glauconite is subangular to subrounded and comprises 30% of the sample (as opposed to 5-10% in the bulk of the facies).

Despite the compositional similarities, the outcrops at Kaikoura and Oaro are physically quite different from one another: at the two Kaikoura sites, the Spyglass Formation is stylobedded, with ~1-4cm thick calcareous glauconitic sandstone interbedded with thicker (0.1-1m), very fine calcarenite. The more recessive nature of the glauconite-rich sands has resulted in a pattern of alternating resistive and recessive beds on a centimetre scale (Fig.2.5a). At Oaro, there are still some centimetre scale, glauconite-rich, silty wisps, but unlike Kaikoura, they do not occur at regular intervals and do not exhibit the same alternating resistive/recessive nature observed in Kaikoura. As a result, the outcrops at Kaikoura and Oaro look completely dissimilar.

The rocks at Kaikoura are extremely well indurated, whereas the rocks at Oaro are generally much less so. These substantial differences, including induration, unit thickness and stylolite formation at Kaikoura are due to the complex burial history which occurred on the Kaikoura Peninsula. The complex folding (Fig. 2.5a) and faulting observed at Kaikoura, but absent at Oaro, is evidence for this event. This lithofacies grades southernwards into the Foraminifera Wackestone at Gore Bay.

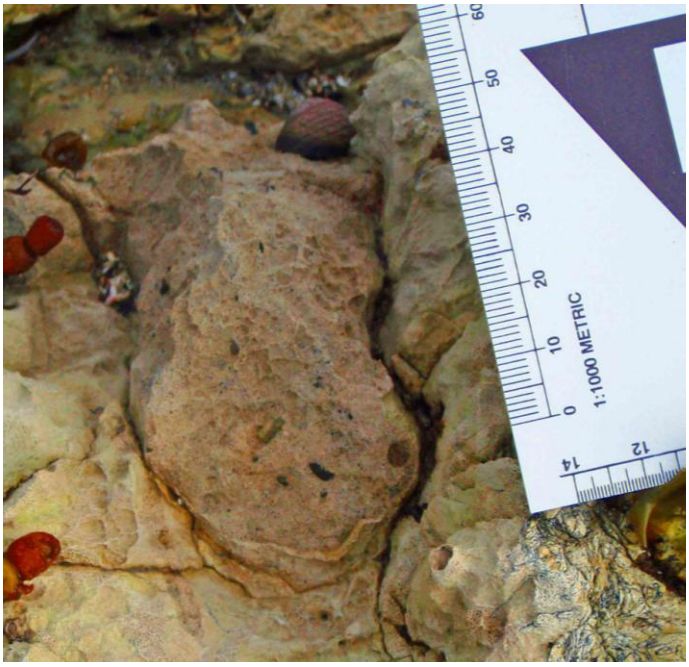


Figure 2.6 *Thalassinoides* burrow at Point Keen, Kaikoura. Burrow is infilled with a pink, very fine sand.

Muddy Quartz Sandstone

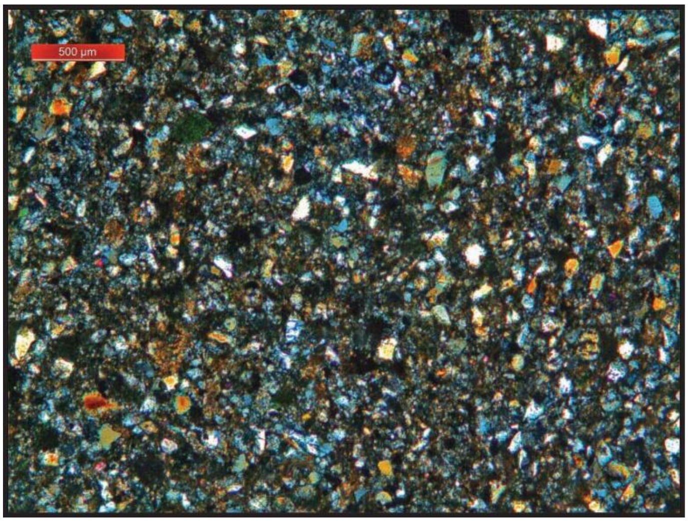


Figure 2.7 Representative thin section from sample JI24. Outcrop picture not available.

Overview

Occurrence: Mendip Hills 42°33'32"S 173°17'15"E

Carbonates: 32% Siliciclastics: 63%

Glauconite: 5% Planktic/benthic forams: 57:43

At the Mendip Hills Farm location (Fig. 2.1), the basal Motunau Group is a muddy fine sandstone, as opposed to the limestone found in the basal Motunau at the coastal locations (Gore Bay, Oaro, Kaikoura and Cribb Creek). The lithofacies is well cemented, poorly sorted and quartz-rich. Glauconite content remained at 2-5% throughout the section.

Thin section analysis of sample JI24, midway up the section, shows that carbonate (exclusively micrite) makes up 32% of the sample. The non-carbonate fraction includes quartz (57% of the entire sample), glauconite (5%), as well as trace amounts of mica (3%), elongate calcite grains (3%), feldspar (1%) and unidentified fragments (1%). No fossils or fragments were observed, which is consistent with the lack of foraminifera found when the sample was sieved. The sample appears to have been diagenetic ally altered, with approximately 60% of the quartz grains showing signs of dissolution along grain edges.

At 7m, a 2m thick calcareous siltstone bed occurred, breaking up the otherwise uniform sandstone. A poorly sorted, fine, cobbley sandstone bed containing 20% angular to subangular, cobble Amuri clasts occurs at 16m. The 25cm horizon was interpreted to be a storm bed which possibly could be correlated with the storm bed seen at Gore Bay, also at 16m above the base of the Motunau Group (discussed in the Impure Wackestone facies).

In total, two samples were collected at the site. Sample JI24 had a thin section cut and was sieved for forams, though none were recovered. Sample JI25, collected from the unique 2m silt bed, was sampled for forams.

Fossiliferous Sandstone

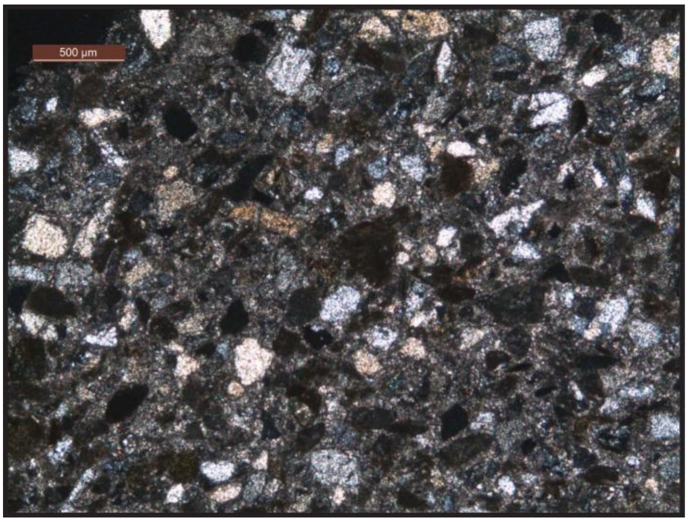


Figure 2.8 Representative thin section of the Fossiliferous Sandstone lithofacies at Mendip Hills. From sample JI2.3. No outcrop picture available.

Overview

Occurrence: Mendip Hills 42°33’07”S 173°16’52”E

Carbonate: 45% Siliciclastics: 51%

Glauconite: 4% Forams: N/A

This fossiliferous sandstone lithofacies, observed only at Mendip, is a quartz-rich, fine sandstone with a glauconite content of ~5%. The lithofacies is highly bioclastic, with fragments of bivalves and other unidentifiable fossils being the most prominent constituents. Many of the fossils and fragments have been replaced by calcite.

Thin section analysis revealed a slight increase in carbonate material from the muddy sandstone lithofacies stratigraphically lower. The sample consists of 45% carbonate and 55% silicates, as opposed to the lower formation which had 33% and 66% respectively. The carbonate content is fossils (2%) and sparry cement (43%). The fossils include bivalves, bryozoans and unidentifiable fragments. The non-carbonate content is composed of quartz (46%), glauconite (4%) and other silicates including micas and feldspar (5%). There are two main quartz components: some of the grains were very fine sand and angular, while the rest were fine-medium sand and very well rounded.

Only one sample (JI23) was collected (Fig. 2.19). It was cut for a thin section and sieved for forams, though none were able to be retrieved.

Impure Wackestone

Figure 2.9 Characteristic outcrop pictures from (a) Kaikoura, (b) Oaro and (c) Gore Bay; thin section picture (d) of the quartz rich wackestone lithofacies from JI29 (Gore Bay).

Overview

Occurrence: Gore Bay 42°52'16"S, 173°3'E; Oaro 42°30'58"S 173°30'27"E;

Kaikoura 42°25'33"S 173°41'33"E

Carbonates: 45-80% Siliciclastics: 15-43%

Glauconite: 2-20% Planktic/benthic forams: 23:2 – 1:0

The upper Motunau Group at the three coastal sites- Gore Bay, Oaro and Kaikoura- is composed of the same lithofacies, a quartz- rich wackestone which extends from the northernmost site (Kaikoura) to the southernmost site (Gore Bay). This lithofacies was not observed extending very far inland; the closest site to the west, Mendip, is a different lithofacies (Fossiliferous Sandstone). The lithofacies is very fine to fine calcareous sand, massive and is generally lacking sedimentary structures. Fossil fragments are observed in concentrated horizons throughout, as is bioturbation, mostly from numerous *Zoophycos* (Fig. 2.10) and occasional *Ophiomorpha.* At Gore Bay only, the lower ~12m is quartz-rich, carbonate-poor and appears to be very similar to the Muddy Quartz Sandstone lithofacies to the north. This carbonate-poor section rapidly transitions into the overall facies, where carbonates are much more predominate (Fig. 2.15).

Thin section analysis show this lithofacies to be a quartz-rich wackestone with varying amounts of carbonate and siliciclastics. Thin sections were taken from four locations at Gore Bay, one location at Oaro and one location at Kaikoura. Sample JI29 from Gore Bay was analysed using the point counter, the rest were via visual approximation. All the samples, except those from the lowermost upper Motunau Group at Gore Bay, contain more than 45% carbonate; the carbonate reaches is highest at Kaikoura with 75%, though it is lower (45-65%) at the other two locations. The exception is the lower 12m at Gore Bay, which contains 30% carbonate. The carbonate fraction is composed mostly of micrite, minor spar, and planktic forams (65-100%). Siliciclastics, made up of very fine-to-fine angular quartz and very minor mica constituents, does not exceed 15% at Kaikoura or Oaro, but reaches as high as 40% at Gore Bay in the upper measured section, and reaches 65% in the lower section. Feldspar and dolomite rhombs are present only in the lower part of Gore Bay. The glauconite content remains at ~10-15% through most of the samples at all locations. At Gore Bay, it decreases to 2% near the top of the measured portion.

Channel-fills were observed within the Gore Bay section, notably one which occurs 16m above the base of the Motunau Group. This 2.5m deep channel is distinguished by an eroded base, along with the occurrence of parallel laminations, fragments of bioclasts (0.5cm-2cm) and subrounded-rounded calcareous clasts from the underlying bed.

Throughout much of the section at Kaikoura which correlates with this lithofacies, sandier beds alternate with silt-rich beds, with the sandier beds tending to be thicker (~0.5-7.0m) than the silty ones (<0.5m). Similarly at Gore Bay and Oaro, an occasional well indurated, very fine sand horizon is present within the sandier, moderately indurated beds.

While the lower ~12m at Gore Bay is similar and time-equivalent to the Muddy Quartz Sandstone lithofacies at Mendip, some notable differences set them apart. The calcite is present exclusively as spar at Gore Bay, and as micrite at Mendip. Percentage of quartz between the two sites is similar (49% vs. 57% respectively), however the occurrence of feldspar, mica and dolomite rhombs at Gore Bay is not observed at Mendip. Foraminifera data, discussed further in Chapter 3, is also substantially different between the two, as 90% of the foraminifera at Gore Bay are planktics, while only 57% Mendip are planktic. The most significant difference which sets them apart is the presence of channels at Gore Bay, which is a feature not observed at the outcrops at Mendip.

In total, 3 samples were collected at Gore Bay, 5 from Oaro and 8 from Kaikoura. From Gore Bay, all three samples, JI 3, 4, 29, were used for petrographic analysis, as well one thin section (GB+30) which had been collected for geochemical purposes. Sample 4 also provided foraminifera specimens, discussed in Chapter 3, though the other two samples did not. At Oaro, the thin section came from sample JI 7. Foraminifera were very difficult to extract, and none could be obtained for this section from any of the samples. At Kaikoura, sample JI16 was cut for a thin section. As at Oaro, the foraminifera were very difficult to extract and none were obtained.

Figure 2.10 Photograph of *Zoophycos* at Kaikoura

Calcareous fine sandstone

Figure 2.11 Characteristic outcrop picture (a) and thin section picture (b) of the calcareous fine grained sandstone lithofacies. a.) Little Lottery River b.) Wandle River, sample JI58. Concretions visible in the outcrop.

Overview

Occurrence: Little Lottery River 42°32’15”S 173°04’30”E; Whale’s Back 42°30’17”S 173°9’52”E; Wandle River 42°35’04”S 173°06’07”E

Carbonates: 49-55% Siliciclastics: 40-48%

Glauconite: 0-15% Planktic/benthic forams: 5:95 – 2:98

The three analyzed inland outcrops of upper Motunau Group are all the same lithofacies, a calcareous fine sandstone. This lithofacies is almost evenly split between calcareous and siliciclastic material, and contains some concentrated horizons of macrofossils and fossil fragments. Organic matter was a prominent component observed at the Whale's Back and Little Lottery River outcrops.

Carbonate material, in the form of sparry cement, makes up 48%, 47% and 49% of Little Lottery River, Wandle River and Whale's Back, respectively. In turn, the siliciclastics comprise 52%, 53% and 51% of the same locations. The clastic minerals are subangular-subrounded and the samples are well sorted. The clastic mineral fraction is dominated by quartz (42% at Whale's Back, 47% at Little Lottery and Wandle River), micas (1.2% at Whale's Back) and feldspar (2.5% at Wandle River). The bioclast percentage is 2% in Little Lottery River and Wandle River, and 5% at Whale's Back. At Wandle River, glauconite percentages alternated between ≤1% (siltstone/concretion layers) and ~10% (sandstone layers). At Little Lottery River, glauconite stay fairly constant, between 2-5% throughout the measured sections. At the base of the Whale's Back section, glauconite started out at 0%, but after a sharp transition, the overlying horizon contained 30% glauconite. The high concentration lasts for 1.5m before lowering back down to ~5%.

Unlike the diagenetically altered, fine quartz grains in the lower Motunau Group Muddy Quartz Sandstone facies, the quartz grains in this upper Motunau Group lithofacies are predominately silt-sized and show no signs of dissolution along the grain boundaries. Calcite is present as spar cement, not micrite, and the foraminifera fauna differ greatly (discussed in Chapter 3). The abundance of organic matter observed at the Whale's Back and Little Lottery River outcrops was not observed in the Muddy Quartz Sandstone facies.

All three locations shared some common characteristics in outcrop, foremost being the presence of very well indurated concretionary horizons. These horizons, averaging 0.2-0.6m thick, are very fine sand - silt, contrasting with the fine-medium sandstones they are interbedded with. They commonly contain large (average ~0.4m, but up to 2.0m in diameter) concretions, or in the least, blocky, rectangular, concretion-like structures. The horizons, occurring at regular intervals on the 1-4m scale, result in a distinctive repetitive pattern visible even from a distance, due to the differential weathering between the two types of beds. According to local residents, fossil fragments are often at the centre of these concretions, though this could not be confirmed.

A second common feature between the locations is the presence of macrofossils, often large and well-preserved. These fossils only occur in some localized horizons within the outcrops. At Whale's Back, the base of the measured section contains numerous phosphatised bivalves (discussed further below); at Little Lottery River, the lower of the two measured sections contained a high spired gastropod, possibly *Turritellid sp*. (Fig. 3.15b), bivalve fragments and a single bivalve, possibly *Cucullaea sp.* (Fig. 2.12b); at the upper section at Little Lottery River, one horizon of parallel laminations was observed to include aligned bivalves and other fragments; at Wandle River, bivalves were observed, though not as commonly as in the other section, possibly as this was a result of simply not measuring one of the "fossil-rich" horizons.

Fissile bedding is also a characteristic of many beds within this lithofacies. The entire measured, section at Whale's Back, with the exception of concretionary horizons, is composed of dark coloured, fissile sand. It is also observed in some horizons at Little Lottery River (such as the horizon where sample JI55 was collected, Fig. 2.21) and Wandle River.

The horizon from which sample JI55 was collected contained interesting features not observed anywhere else. Within the dark coloured, fissile sand was phosphate nodules, phosphatised brachiopods and a very high percentage of glauconite (30%). While the colour and nature of this horizon was homogeneous throughout the section, the high glauconite content and phosphatisation was not.

In total, 6 samples were collected at Little Lottery River, two at Wandle River and three at Whale's Back. Two thin sections were made (JI52, 54) and 3 samples produced enough foraminifera for analysis at Little Lottery; one thin section (JI58) and 1 foraminifera sample from Wandle River; and 1 thin section and 1 foraminifera sample from Whale's Back (JI45).

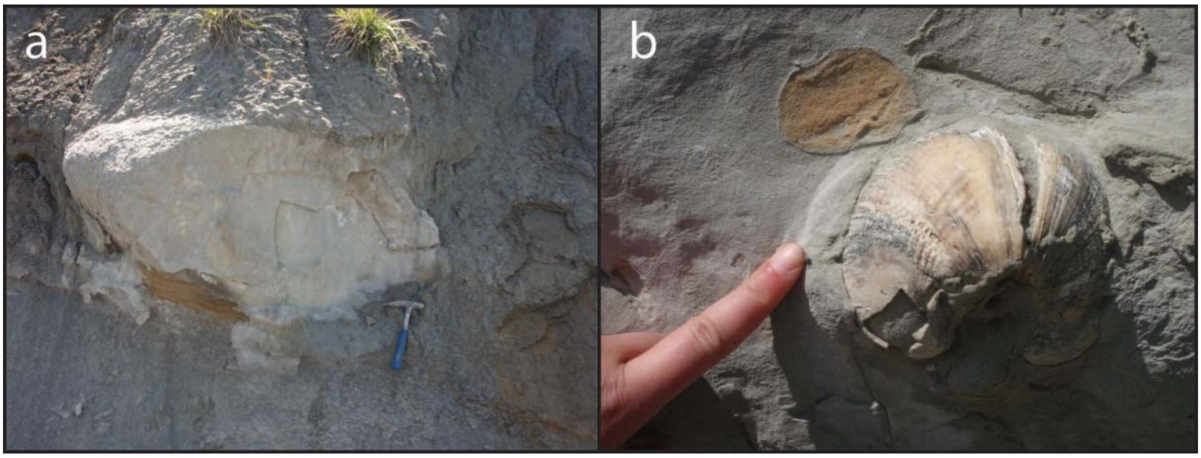


Figure 2.12 Figures from Little Lottery River. a.) Large concretion with hammer for scale b.) Large bivalve, possibly *Cucullaea sp.*

2.4 Stratigraphy

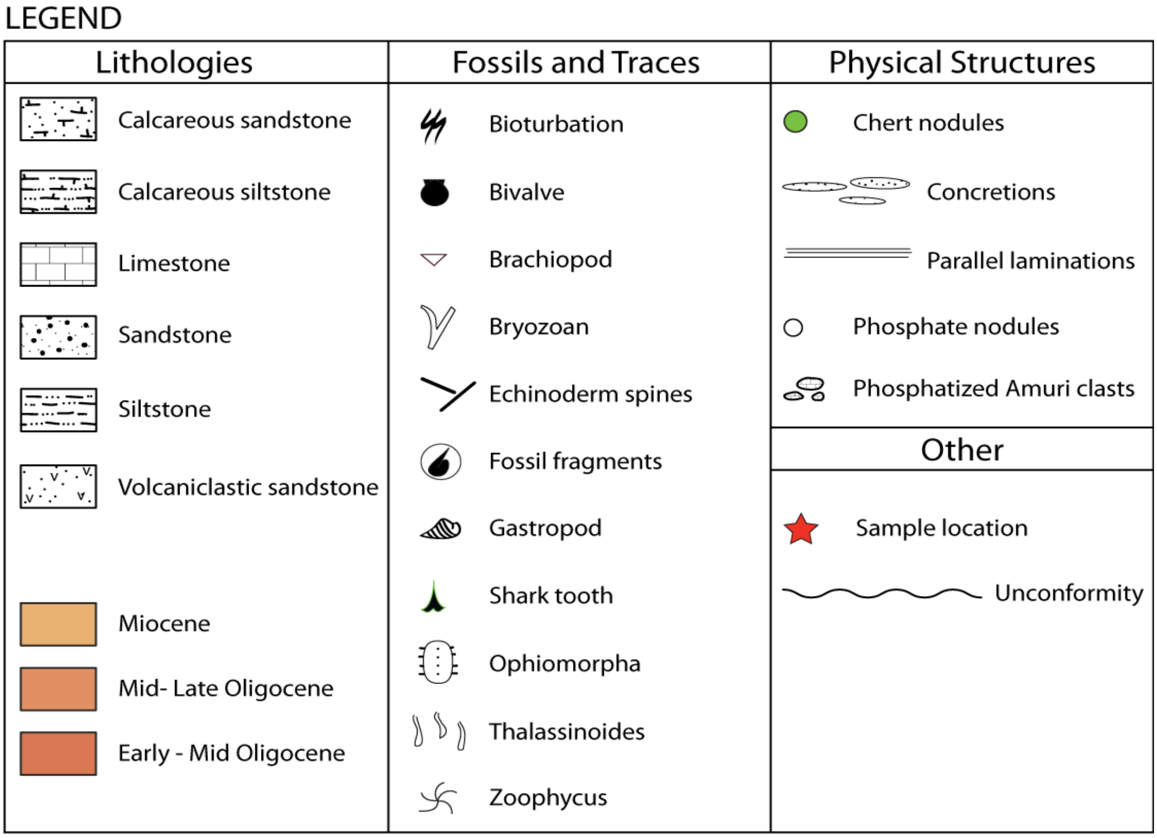


Figure 2.13 Legend of symbols used in the stratigraphic columns

Gore Bay

Gore Bay is the southernmost site (Fig. 2.1), located along the present-day coast line. At this location, the Amuri Limestone, Marshall Paraconformity, Foraminifera Wackestone lithofacies and Impure Wackestone lithofacies are all present.

At the base of the lower Motunau Group is the Marshall Paraconformity, appearing essentially the same as the other locations where it is observed: an erosional surface topped by a 14cm horizon of phosphatised Amuri clasts, ranging in size from medium to very coarse pebble, surrounded by a matrix of fine glauconitic sandstone, which forms the base of this facies. The phosphatised horizon is densely borrowed by *Thalassinoides*, which are infilled with highly glauconitic sand. The *Thalassinoides* burrows often extend down into the Amuri.

This lithofacies is approximately 15m thick, substantially thinner than at Cribb Creek, where it is 60m thick. These rocks are included in the undifferentiated lower Motunau Group, equivalent to the Spyglass Formation found to the north at Kaikoura.

Overlying the Foraminifera Wackestone is the Impure Wackestone lithofacies. The two lithofacies are separated by a sharp contact, though the surface appears to be conformable. These rocks are designated by Rattenbury et al (2006) as the Waikari Formation, and are equivalent to the Waima Formation to the north. Only the lowermost portion (40m) of this Formation is observed and measured, as it has been measured to be up to 360m thick in some locations (Rattenbury et al., 2006). The lower 12m of this lithofacies is much more siliciclastic-rich and shows some similarities to the Muddy Sandstone lithofacies to the north at Mendip.

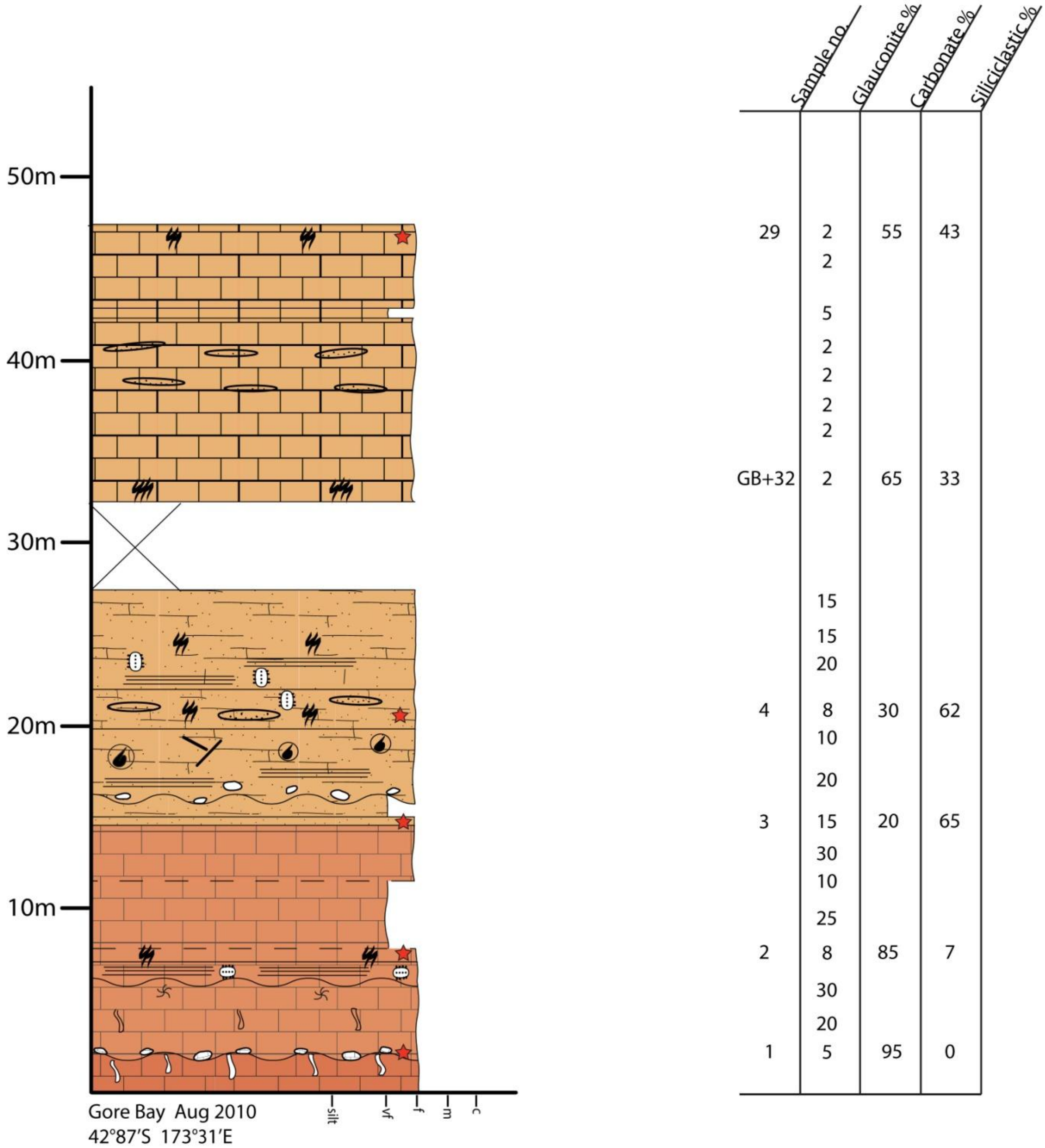


Figure 2.14 Stratigraphic column of Gore Bay with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.13 for Key

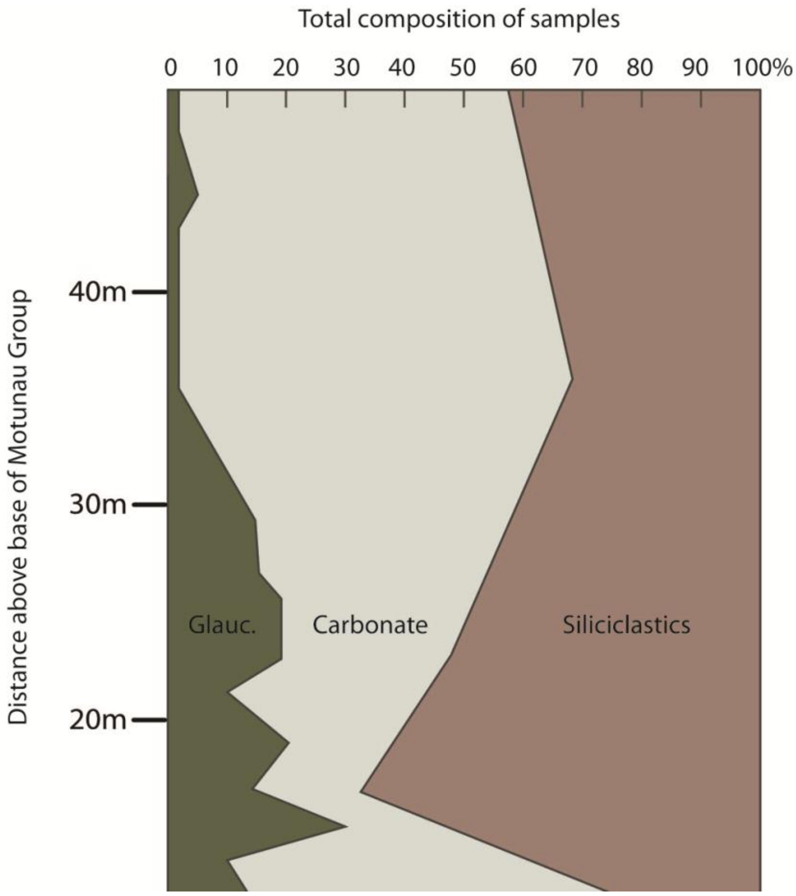


Figure 2.15 Schematic diagram of the changes between glauconite, carbonate and siliciclastic content of the upper Motuau Group at Gore Bay up through the section. Y-axis is distance from base of Motunau Group.

Oaro

Located at the bottom of the measured section occurs the uppermost portion of Amuri Limestone, a biomicrite with ~5% glauconite. A 20cm layer of phosphatised chalk nodules, up to 3cm in size, rests on the Paraconformity and forms the base of this lithofacies. The highly glauconitic sand matrix is heavily bioturbated, many of which penetrate the Amuri Limestone.

A sharp contact separates the phosphatised horizon from the remainder of the Foraminifera Packstone lithofacies, which is made up of the Spyglass Formation of the lower Motunau Group. The thickness of this formation varies, measuring 9m at Oaro, which is substantially less thick than the 50m section at South Bay Kaikoura

This lithofacies is directly overlain by the Impure Wackestone lithofacies, with a sharp, though apparently conformable, contact separating the two. The rocks in this lithofacies are part of the lowermost Waima Formation of the upper Motunau Group. Only the lowermost portion (25m) of this Formation is observed and measured, as it has been measured to be up to 360m thick in some locations (Rattenbury et al., 2006).

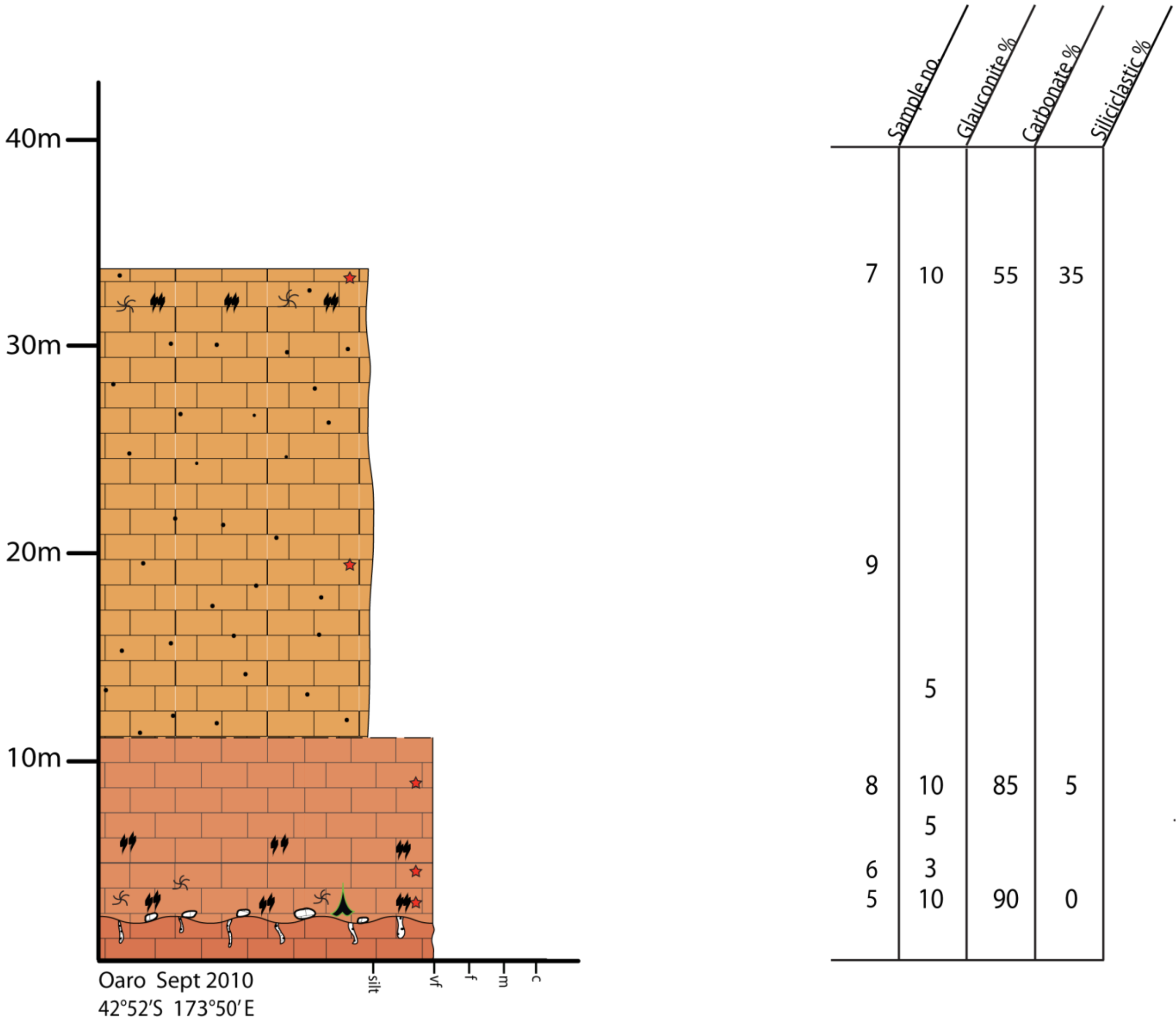


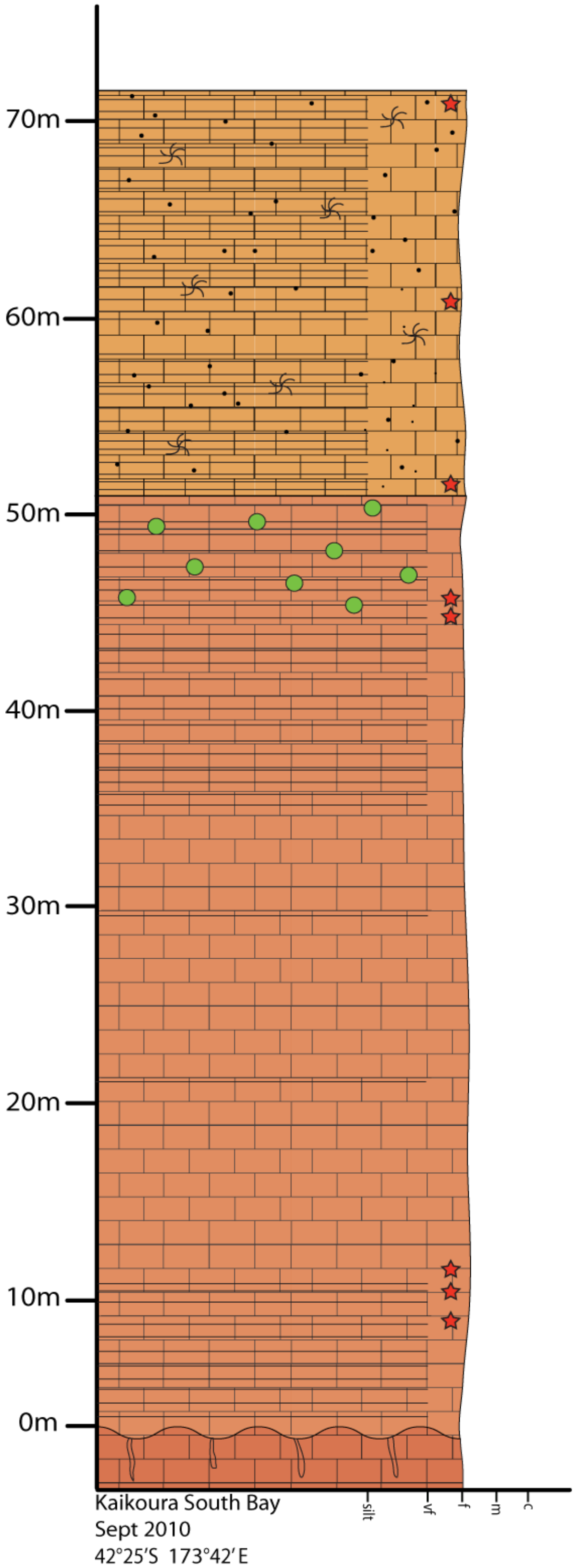
Figure 2.16 Stratigraphic column of Oaro with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.13 for Key.

Kaikoura

Two outcrop locations at Kaikoura were measured: South Bay and Point Keen. Kaikoura is the northern-most coastal site in this field area. Located at the bottom of the measured section occurs the Amuri Limestone, a biomicrite with ~1-5% glauconite which is truncated by the Paraconformity. The typical 15-20cm layer of phosphatised chalk nodules, up to 3cm in size, overlies the Paraconformity and forms the base of this lithofacies. The highly glauconitic sand matrix is heavily bioturbated, with some burrows up to 6cm across (Fig. 2.6). The burrows are infilled with a very fine, pink coloured sand.

A sharp contact separates the phosphatised layer from the overlying Foraminifera Packstone, which is made up of the Spyglass Formation of the lower Motunau Group. The thickness of the Formation substantially different between the two sites; the outcrop at South Bay is ~50m, 11m at Point Keen.

This lithofacies is directly overlain by the Impure Wackestone lithofacies, separated by a sharp, conformable contact. The rocks in this lithofacies are part of the lowermost Waima Formation of the upper Motunau Group. Only the lowermost portion (20m) of this Formation is observed and measured, as it has been measured to be up to 360m thick in some locations (Rattenbury et al., 2006).



Sample no.	Glauconite %	Carbonate %	Siliciclastic %
17			
16	10	75	15
15	15		
14	4	95	1
13	9	90	1
12	5	94	1
11	5	90	1
10	30	60	5

Figure 2.17 Stratigraphic column of Kaikoura South Bay with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.13 for Key.

Cribb Creek

Cribb Creek is the northernmost site (Fig. 2.1), located 15km inland of Kaikoura. At this location, the Amuri Limestone, Marshall Paraconformity and Foraminifera Wackestone lithofacies are present.

At the base of the lower Motunau Group is the Marshall Paraconformity, overlain buy the characteristic phosphatised layer, which appears essentially the same as the other locations where it is observed: a 10cm horizon of phosphatised Amuri clasts, up to 5cm in diameter, surrounded by a matrix of fine glauconitic sandstone. The sandstone is densely borrowed by *Thalassinoides*, which are infilled with highly glauconitic sand. The *Thalassinoides* burrows extend 1.2m into the Amuri Limestone.

A sharp contact separates the phosphatised layer from the remainder of the overlying Foraminifera Wackestone lithofacies. This lithofacies is approximately 60m thick, substantially thicker than at Gore Bay, where it is 15m thick. These rocks are included in the undifferentiated lower Motunau Group, equivalent to the Spyglass Formation found at Kaikoura.

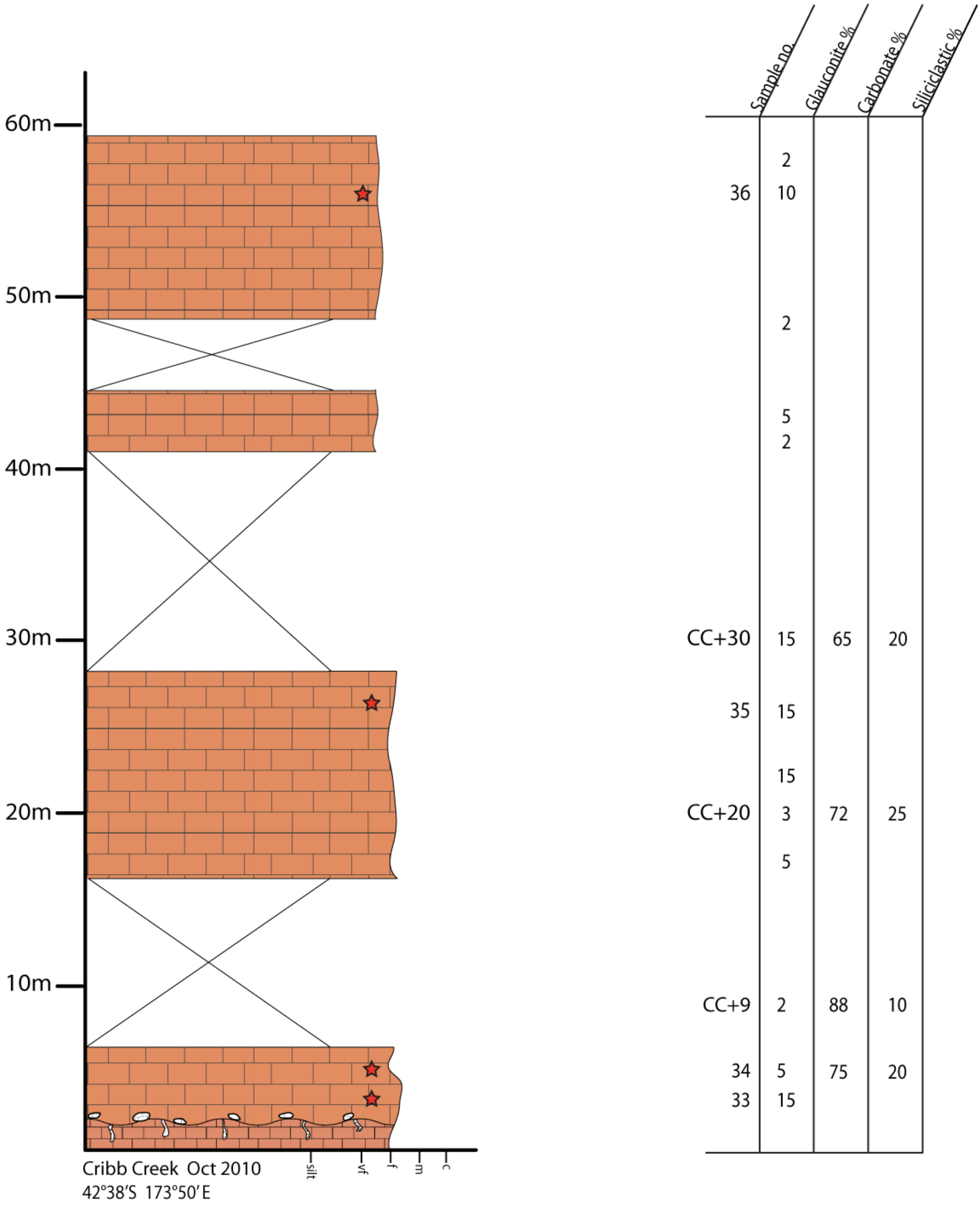


Figure 2.18 Stratigraphic column of Cribb Creek with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.14 for Key.

Mendip

The Mendip Hills location is located ~18km inland, west of Oaro. The section measured was an outcrop exposed along a hillside where a farm track has been cut; in total, ~45m was exposed and measured, beginning ~2m above the Paraconformity.

The Marshall Paraconformity and the associated phosphatised layer, observed at different locations in the vicinity, is comparable to all other locations examined. The top of the Amuri is a very pure packstone full of *Thalassinoides* burrows, which are infilled with both chalk and glauconite-rich sands. The overlying the Paraconformity is a 0.1m horizon of glauconitized Amuri clasts, forming the base of this lithofacies. Directly overlying the Marshall Paraconformity is the Muddy Sandstone lithofacies, which is part of the undifferentiated lower Motunau Group.

Overlying the Muddy Sandstone is the Fossiliferous Sandstone. This lithofacies appears to be the northernmost extent of the Mount Brown Formation (Jongens et al., 2008). The contact between this lithofacies and the previous was not observed. The outcrops are small, discrete and possibly separated by faults, so no attempt was made to measure a stratigraphic section. Observations from the various outcrop locations were noted and amalgamated.

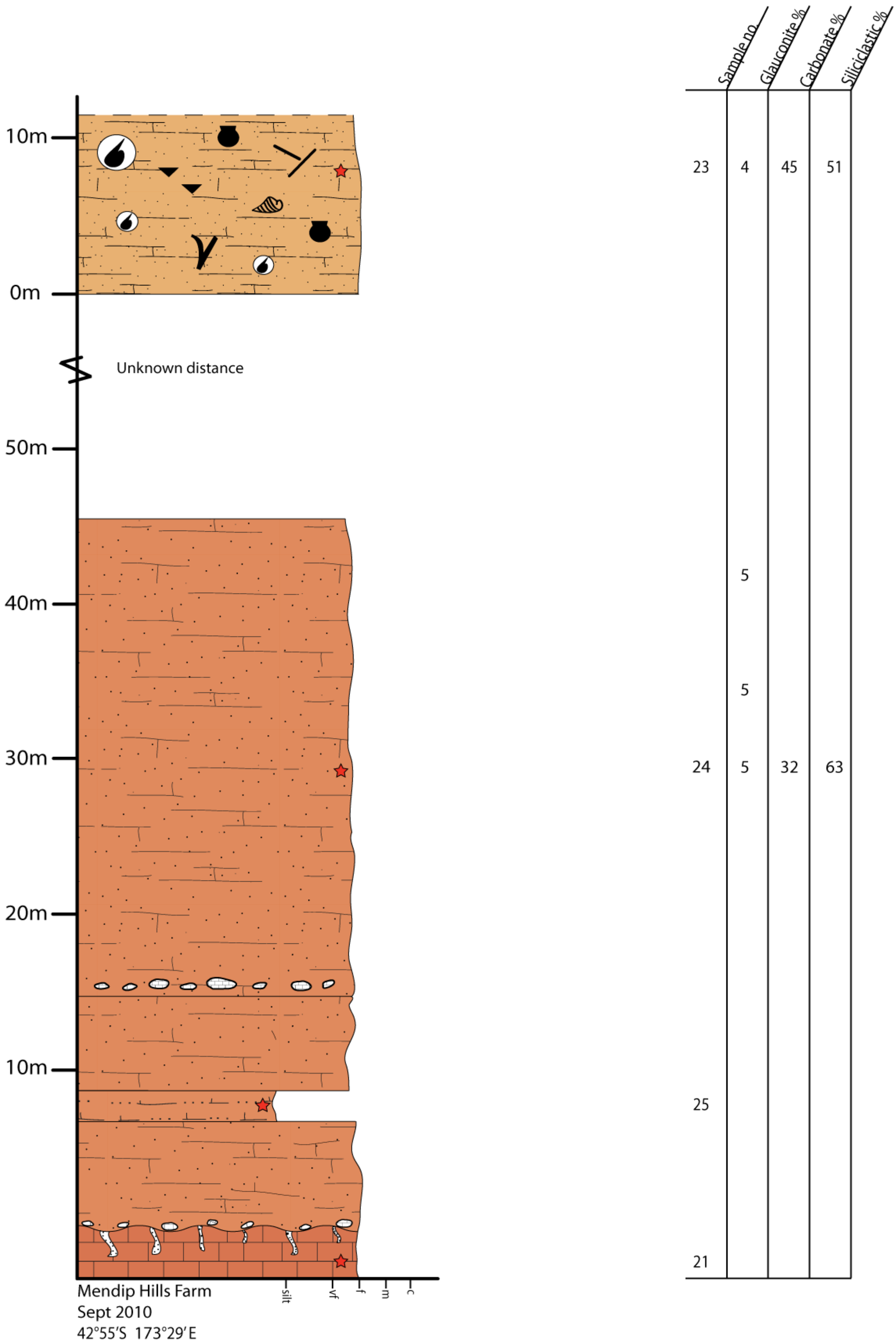


Figure 2.19 Stratigraphic column of Mendip Hills area with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.13 for Key.

Whale's Back

The Whale's Back location is located 26km north of the town of Waiau. The Marshall Paraconformity was not observed in outcrop at this location, though its existence in the region is assumed from observations of it at nearby locations, such as Little Lottery River.

From outcrop investigation, it appears the Volcaniclastic Calcareous Sandstone lithofacies directly overlies the Marshall Paraconformity, though it is not know how far above the Paraconformity the measured outcrop was located. The lithofacies has a limited extent across the field area and was only observed along a 30m outcrop. The rocks from this lithofacies are part of the Cookson Volcanics of the lower Motunau Group.

Overlying the Volcaniclastic Calcareous Sandstone lithofacies is the Calcareous Fine Sandstone lithofacies. The contact between the two was not observed. This lithofacies is part of the undifferentiated upper Motunau Group and is stratigraphically above the Impure Wackestone lithofacies seen to the east. The sections' location with respect to the Marshall Paraconformity was unknown, since the boundary was never observed in the area.

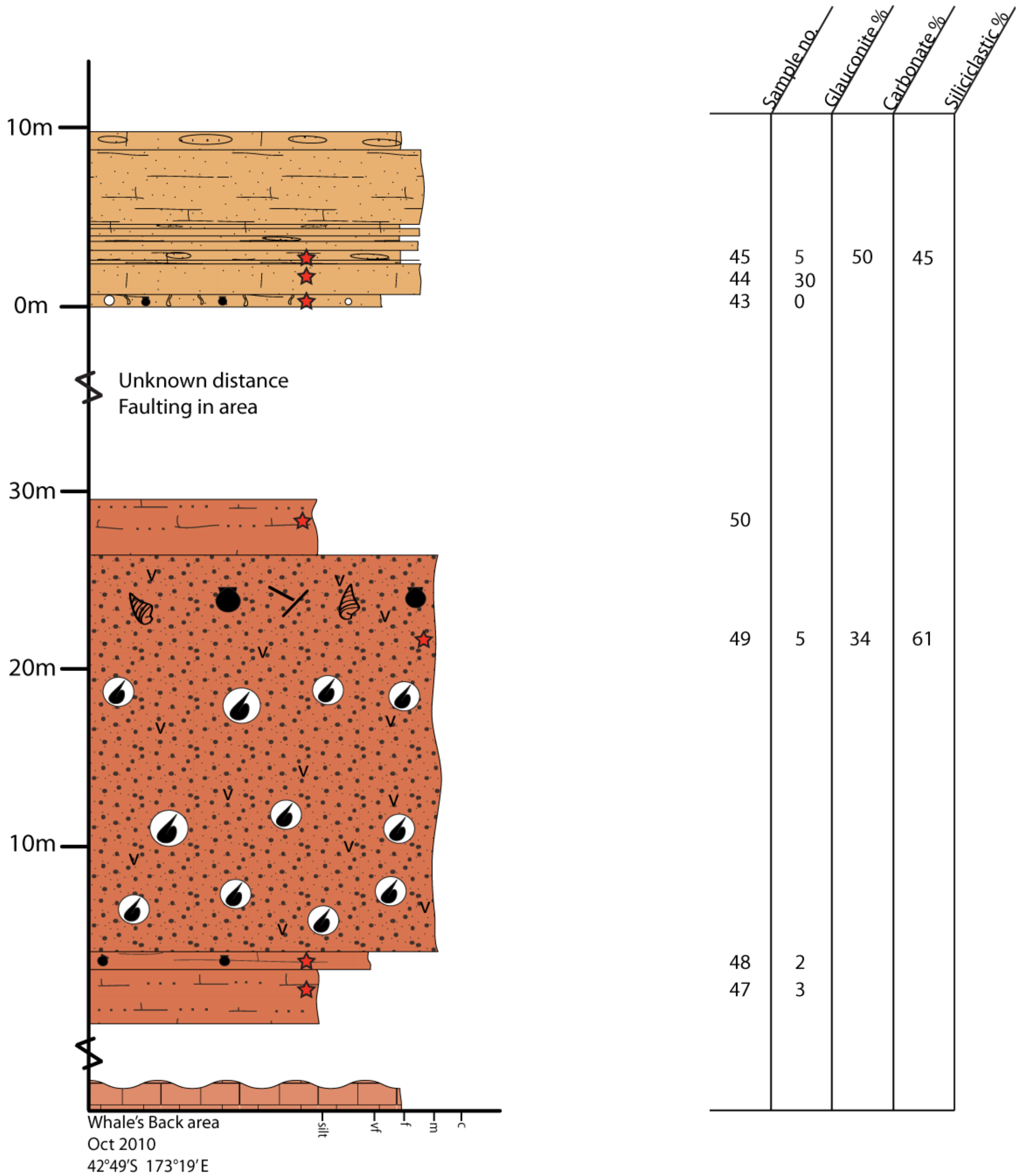


Figure 2.20 Stratigraphic column of Whale's Back with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.14 for Key.

Little Lottery River

The Little Lottery River location is the westernmost site, situated to the south of Whale's Back and north of the Wandle River location. The sections' location with respect to the Marshall Paraconformity was unknown, since the boundary was never observed in the area.

The lithofacies observed at this location is the Calcareous Fine Sandstone, as also seen at Whale's Back and Wandle River. This measured section is part of the undifferentiated upper Motunau Group and is equivalent to the uppermost Waima Formation seen in Kaikoura (Fig. 1.1). A combination of the unit's thickness and the lack of continuous outcrop meant that only short, discrete sections were measure in the field.

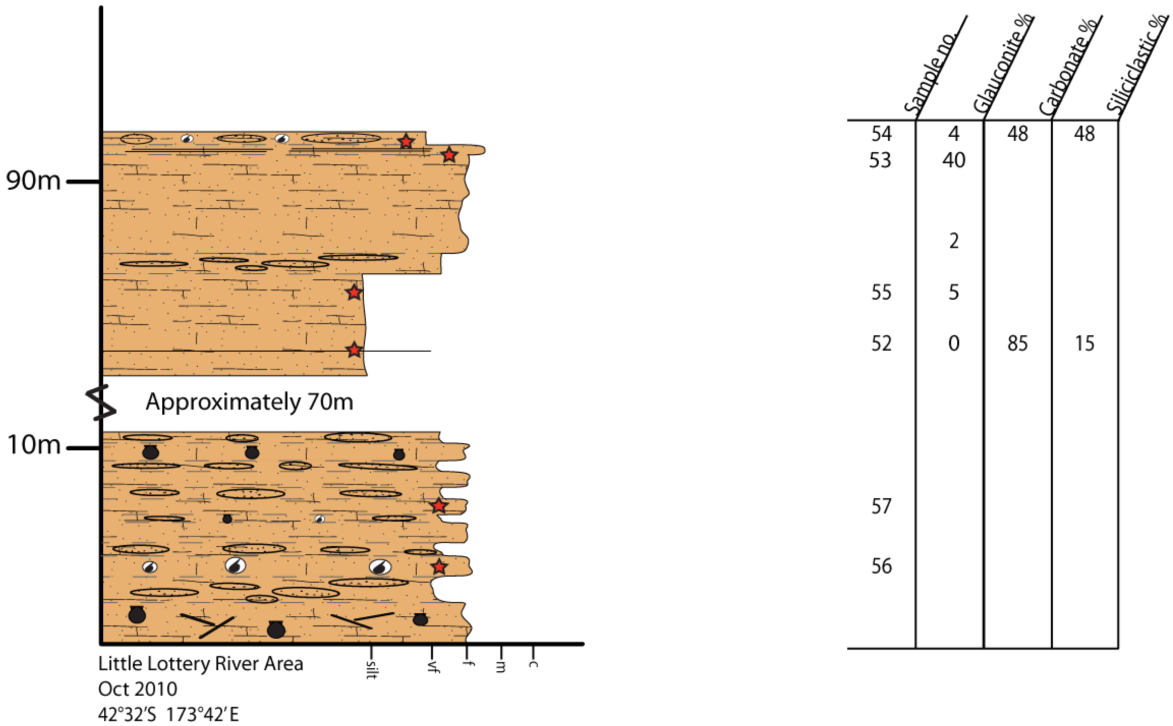


Figure 2.21 Stratigraphic column of Little Lottery River area with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.13 for Key.

Wandle River

The Wandle River location is situated in the south-west corner of the field area. As with the Little Lottery River location, the only lithofacies observed here is the Calcareous Fine Sandstone, included in the undifferentiated upper Motunau Group. Its location with respect to the Marshall Paraconformity is unknown, as the boundary is not observed at this location.

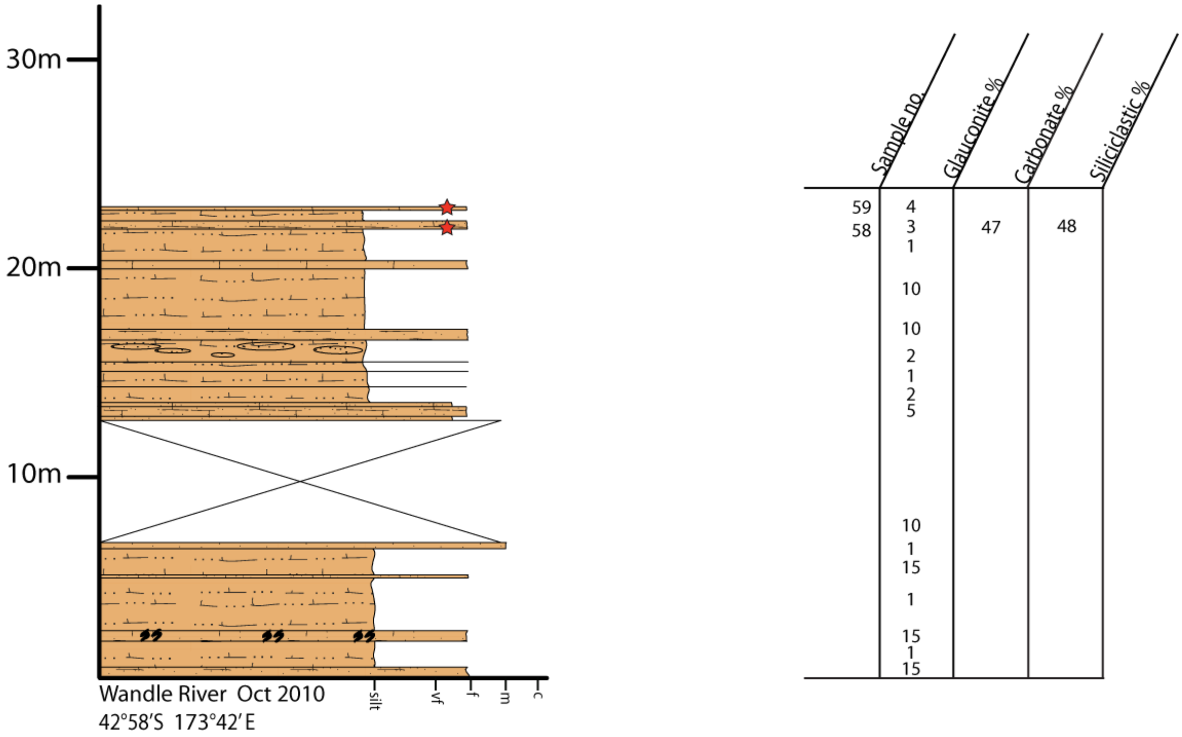


Figure 2.22 Stratigraphic column of Wandle River with corresponding values of glauconite, carbonate and siliciclastics. Refer to Fig. 2.13 for Key.

Summary

In total, seven lithofacies were recognized across this field area: a calcareous volcaniclastic sandstone, foraminiferal wackestone, foraminifera packstone , muddy sandstone, quartz-rich wackestone, calcareous fine sandstone and a fossiliferous sandstone. In general, limestones occur stratigraphically lower, while sandstones occur higher. At all locations where the transition from Eocene Amuri Limestone to Oligocene limestone occurs, the Marshall Paraconformity is present. Its characteristic features remain consistent throughout the field area.

Sedimentological features, as well as fossils, were rare in the observed sections. Foraminifera are the most common fossil; eastern sites are dominated by planktic forams, while sites to the west are dominated by benthic forams.

3 MICROPALAEONTOLOGY AND BIOSTRATIGRAPHY

3.1 Introduction

One of the main goals of this project was to determine the ages of the various samples collected along the measured sections; this was done using foraminifera biostratigraphy. In total, fifty samples were collected along the measured sections for foraminifera work, however the absence of foraminifera or their poor preservation meant that only thirteen of the selected samples yielded workable foraminiferal faunas.

3.2 Methods

Foraminifera processing

Processing procedures followed the basic outline given in Hornibrook et al. (1989). Fist-sized samples were crushed by a hand press before being submerged in 5% hydrogen peroxide. The bubbling action of the peroxide was sufficient to disaggregate most of the samples within 60 minutes, though a few samples had to be heated for further 60 minutes before disaggregating. Using a 65μm mesh, the samples were then sieved and placed in a 50°C oven to dry out. Between individual samples being processed, each piece of equipment (the press, bowl and sieve) were dipped into methylene blue (a $CaCO_3$ stain) to trace any contamination between samples.

Disaggregated samples were split using a sample splitter, and a small split was poured on to a gridded picking tray numbered 1-100. Following the random number order on a list generated by *random.org*, the squares were carefully inspected for foraminifera or foraminifera fragments. All foraminifera within the square were picked before moving on to the next randomly designated square. The foraminifera were placed onto a slide and glued down with gum tragacanth. Other biofragments, if observed, were also collected and grouped together to help in the identification of palaeoenvironments. In most samples, a total of 100 specimens were picked, only one sample (54) did not contain a high enough density of foraminifera to reach 100. During the picking process, 2 foraminifera were found to have been stained by the methylene blue and were consequently discarded.

Foraminifera identification

Foraminifera specimens were identified to the species level wherever possible. The main texts used to aid the identification were *Manual of New Zealand Permian to Pleistocene Foraminiferal Biostratigraphy* (Hornibrook et al., 1989) and *Tertiary Foraminifera of the Oamaru District* (Hornibrook, 1961). Due to variable preservation within the samples, it was not always possible to resolve specimens to specific level. Therefore, some taxa are reported to the genus level or simply as “benthic”.

Planktic foraminifera proved to be much more difficult. The majority of the samples contained planktic foraminifera which were too poorly preserved to be able to identify to the species, or even genus, level. The specimens were identified where possible, but the rest were included only in the planktic-to-benthic ratio and were not used for age determination. Diversity indices, which were produced and included in the following section, were affected by the poor level of preservation due to the limitations on identifying specimens. Even though the exact diversity numbers will be somewhat misleading, the indices are still relevant when compared amongst the sample set, as this problem effects the majority or the samples.

The age of each sample was determined by finding the area of overlap between the age distribution of all the foraminifera species present in the sample. For many of the samples, this was resolved to the Stage level. The following diagram, depicting the New Zealand Cenozoic time scale, modified from Hollis et al. (2010), was used when applying Stages to the determined ages, as it is the most recent version of New Zealand’s geologic time scale currently available.

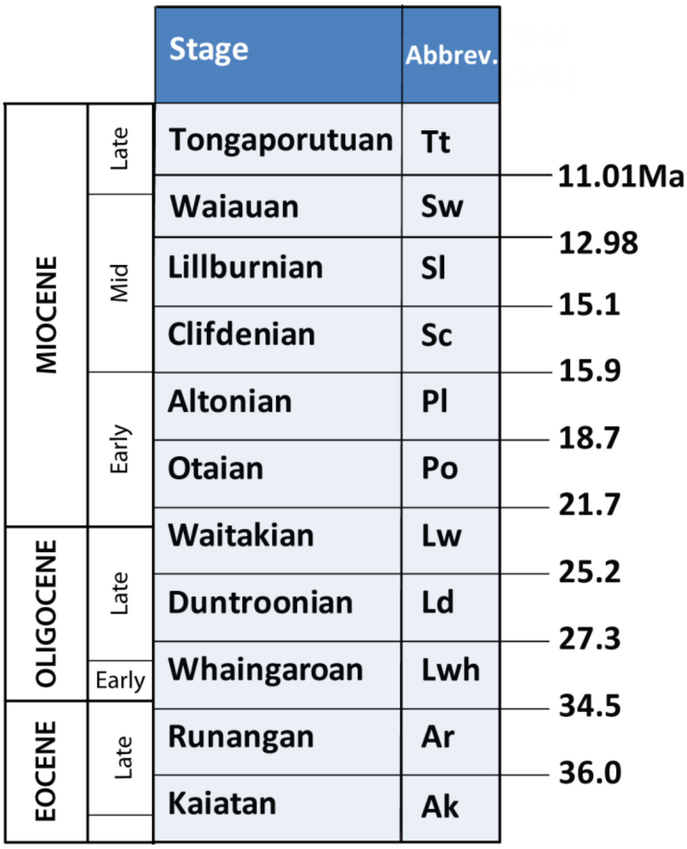


Figure 3.1 New Zealand Cenozoic time scale. Modified from Hollis et al. (2010).

Statistical analysis

Diversity indices were run on all samples using the statistical program Palaeontological Statistics, or PAST (Hammer et al., 2004). The purpose of calculating biodiversity indices is to “make a quantitative estimate of the biodiversity of a community based on a sample from the once-living community” (Hammer et al., 2004). There exists a wide variety of biodiversity indices to chose from when analyzing a data set, from which five common indices were chosen for this project, described below. Additionally, effective number of species (true diversity) was calculated for one of the indices, Shannon-Weiner. This was done in order to better compare differences between sample sets. Results from raw diversity indices cannot be directly compared to one another, because they are non-linear with respect to diversity (Jost, 2006). When converted to effective species numbers, the data can then be compared against each other to accurately define changes. The effective number is given below, behind the raw data in parenthesis.

The data required to perform these analysis was a specimen count, done while identifying the samples, which is included in the following sample results.

Richness (S): The number of species and/or genera in a sample.

Dominance (D): The degree to which one species is more numerous than the other species in a community or sample.

Evenness(E): Quantifies numerically how similar the abundances of different species in a community is. A community where all species are equally or nearly equally represented has a high evenness. The value of E is constrained between 0 and 1; a higher value of E indicates higher evenness.

$$E = H/\ln(S)$$

Shannon-Wiener index (H): A measure of entropy in a data set. The value of H will approach zero as diversity decreases, with more specimens belonging to a singular dominant group, even if there are many groups. Shannon diversity is the fairest diversity measure, weighing each species exactly by its frequency, not favoring either rare or common species. (Jost, 2006). Higher values are indicative of higher diversity (Hammer and Harper, 2006).

$H = -\Sigma p_i \ln p_i$ *Where* p_i *is the proportion of the assemblage made up of species i.*

Effective number of species was calculated using the formula e^H and is included in parenthesis behind the value of H.

Simpson Diversity index (D): Similar to the Shannon-Wiener index, the Simpson Diversity index indicates the probability that two randomly selected individuals belong to a different species. It takes into account both richness and proportion of each species. The value will be close to one if there is a single dominant taxa; decreases with increasing evenness. The value of D is constrained between 0 and 1, with higher values corresponding to higher diversity.

$$\mathbf{1- D = 1 - \Sigma} \boldsymbol{p_i^2}$$

3.3 Results of Foraminifera Analysis

The following results are organized by stratigraphic section, working up section at each location. Species are organized by Order.

Gore Bay

Sample JI 1

Planktics: 69% Age: Lower Waitakian (*Globoturborotalia woodi* zone, ~23Ma)

Diversity indices: S= 22 D= 0.266 E= 0.352 H= 2.047 (7.74) D= 0.734

This sample was collected at Gore Bay (see Fig 2.1) , 0.1m above the Marshall Paraconformity from limestone of the basal Motunau Group (Fig 2.14) in the Foraminifera Wackestone facies. The assemblage is predominantly planktic, with the sample consisting of 69% planktics and 31% benthics. Of the 69 planktic specimens, only 20 were identified to the species level due to poor preservation. Four species of planktics were recognized; the remainder were predominantly globigerines.

There were 12 benthic species and 5 taxa identified to the genus level. The most common benthic genera are *Cibicides* (3 species, 15% of sample) and *Lenticulina* (2 species, 4% of sample). The statistics show low-medium dominance, low evenness (E= 0.35) and average diversity (H= 2.05). These values are misleading though, as they take into account the huge proportion of unidentified planktic foraminifera (49/100) as one group equal to each other species. When this value is disregarded, dominance becomes extremely low, evenness increases and effective diversity increases by a factor of 1.8.

The age of this sample is Lower Waitakian (Fig. 3.2) The upper age limit is constrained by *Planulina renzi, Rectuvigerina rerensis, Vulvulina pennulata, Globorotalia mayeri psuedocontinuosa* and *Globoturborotalia woodi connecta.* The lower age limit is constrained by *Globigerina euapertura.*

	Age range	D	Ab	Ak	Ar	Lwh	Ld	L.Lw	U.Lw	Po	Pl	Sc	Sl	Sw		R	%
1	*Dorthia minima*																1
2	*Vulvulina pennatula*																1
3	*agglutinated sp.*																1
4	*Textulariida sp.*																1
5	*Lenticulina gyroscalpra*																1
6	*Lenticulina pusilla*																2
7	*Lenticulina sp.*																1
8	*Planulina renzi*																1
9	*Anomalinoides orbiculus*																2
10	*Cibicides notocenicus*																1
11	*Cibicides novozelandicus*																7
12	*Cibicides temperata*																6
13	*Cibicides sp.*																1
14	*Gavelinella zealandica*																1
15	*Notorotalia sp.*																1
16	*Rectuvigerina rerensis*																2
17	*Bolivinopsis cubensis*																1
18	*Globigerina euapertura*																2
19	*Globoturborotalia woodi connecta*																11
20	*Globorotalia mayeri pseudocontinuosa*																4
21	*Globorotalia mayeri semiverva*																3
	Unidentified planktics																49
	Total																**100**

Figure 3.2 Foraminifera in sample 1 (from Gore Bay), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

<u>Sample JI 2</u>

Planktics: 71% Age: Lower Waitakian (*Globoturborotalia woodi* zone, ~23Ma)

Diversity indices: S= 23 D= 0.232 E= 0.393 H= 2.047 (7.74) D= 0.768

This sample, from Gore Bay, was collected approximately 7m above the base of the Motunau Group (refer to stratigraphic column, Fig. 2.14) from the Foraminifera Wackestone facies. This sample has many of the same attributes as JI1. The percent of planktics is essentially unchanged at 71%, and many of the species present have remained the same. Dominance was low, with most species making up 1-3% of the assemblage; the main constituents are *Globigerina eurapertura* (14%) and *Cibicides* (3 species, 12% of the sample).

Identification of benthics to the species level was possible with 12 taxa; due to preservation quality, identification was possible only to the genus level with 2 specimens as well as a further 2 specimens which could only be identified as being benthic. Seven planktic species, totalling 26 specimens, were identified. The remaining 46 specimens were not identified due to preservation quality.

The statistics are essentially unchanged from JI1: the sample has low dominance (D=0.23), low evenness (E=0.39) and medium diversity (H=2.05). The same problem exists for this sample that did for JI1 however; the large value of unidentified planktics (45/100) means the values are somewhat misleading. Disregarding the unidentified planktics, the dominance decreases greatly, evenness increases and the effective Shannon index increases 2x, which is the highest value of any of the other samples.

The age of this sample is Lower Waitakian. The upper age limit is constrained by *Siphotextularia awamoana*, *Globoquadrina dehiscens* and *Globoturborotalia woodi connecta*. The lower age limit is constrained by *Globigerina euapertura* and *Globigerina labiacrassata*.

	Age range	D	Ab	Ak	Ar	L.Lwh	U.Lwh	Ld	L.Lw	U.Lw	Po	Pl	Sc	Sl	Sw		R	%
1	*Karreriella novozealandica*																	2
2	*Siphotextularia awamoana*																	1
3	*Amphicoryna hirsuta*																	1
4	*Laevidentalina filiformis*																	1
5	*Lenticulina pusilla*																	1
6	*Planularia halophora*																	3
7	*Cibicides notocenicus*																	3
8	*Cibicides novozelandicus*																	2
9	*Cibicides temperata*																	3
10	*Cibicides sp.*																	4
11	*Gyroidinoides zelandicus*																	1
12	*Siphonina australias*																	2
13	*Bolivina pontis-anastomosa intermediate*																	1
14	*Bolivina sp.*																	2
15	*Globigerina c. ciperoensis*																	1
16	*Globigerina euapertura*																	14
17	*Globigerina labiacrassata*																	2
18	*Globoturborotalia woodi connecta*																	4
19	*Globoquadrina dehiscens*																	2
20	*Globoquadrina tripartita*																	2
21	*Globorotalia mayeri psedocontinuosa*																	1
	Unknown benthics																	2
	Unknown planktics																	45
	Total																	**100**

Figure 3.3 Foraminifera in sample 2 (from Gore Bay), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

Sample JI 4

Planktics: 90% Age: Waitakian-Altonian (25.2-15.9Ma)

Diversity indices: S= 7 D= 0.812 E= 0.234 H= 0.495 (1.64) D= 0.188

The third foraminifera sample examined from Gore Bay, collected 20m stratigraphically above the base of the Motunau Group from the Impure Wackestone lithofacies (2.15), shows a substantial increase in the planktic/benthic ratio from the two lower samples. Planktics make up 90% of the sample, though are preserved only as unidentifiable fragments. Benthic comprise 5 species. Cibicides (*C. perforatus* and *C. temperata*) makes up 4% of the entire sample, while infaunal species (*Chrysalogonium verticale* and *Laevidentalina filiformis*) make up 4%.

Statistical analysis of this sample is essentially ineffective, as 90% of the sample has been grouped into one category, “unknown planktics”. This has skewed the data to appear one group in the sample is highly dominant, and that there is less diversity than there would be in reality if these foraminifera had been identified.

The precise age of this sample was difficult to constrain, however the upper age limit is given by *Chrysalogonium verticale*, and the lower age is limited by the age of the underlying samples (JI1 and 2, Lower Waitakian), indicating a broad Waitakian to Altonian age.

	Age range	D	Ab	Ak	Ar	Lwh	Ld	Lw	Po	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp		R	%
1	*Chrysalogonium verticale*																			1
2	*Laevidentalina filiformis*																			3
3	*Cibicides perforatus*																			2
4	*Cibicides temperata*																			2
5	*Nonionella novozealandica*																			1
	Unknown benthics																			1
	Unknown planktics																			90
	Total																			100

Figure 3.4 Foraminifera in sample 4 (from Gore Bay), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

Gore Bay Quarry

<u>Sample JI 28</u>

Planktics: 82% Age: Waitakian (25.2 - 21.7Ma)

Diversity indices: S= 13 D= 0.555 E= 0.249 H= 1.173 (3.23) D= 0.444

This sample was collected 0.1m above the base of the Motunau Group in the Foraminifera Wackestone facies, from a site approximately 10km inland of Gore Bay (Fig 2.1). The percentage of planktics is slightly higher in this assemblage than the equivalent stratigraphic position at Gore Bay (JI1), with 82% planktics and 18% benthics. The diversity of benthic species is substantially lower than JI1, with only 8 species observed. All benthic specimens were identified to the species level; the genus *Cibicides* was the most common, with three species (C. *novozelandicus, notocenicus and temperata*) making up 9% of the sample. Infaunal species (*Chrysalogonium vertical*, *Karreriella novozealandica* and *Stilostomella fijiensis*) made up a further 6%. The same issues with the statistics of the previous samples occurs as well here, due to the high percentage of unidentified planktics.

The age of this sample is Waitakian, with the upper age limit constrained by *Karreriella novozealandica* (Fig. 3.6) and the lower by *Globoturborotalia woodi connecta* (Fig. 3.7).

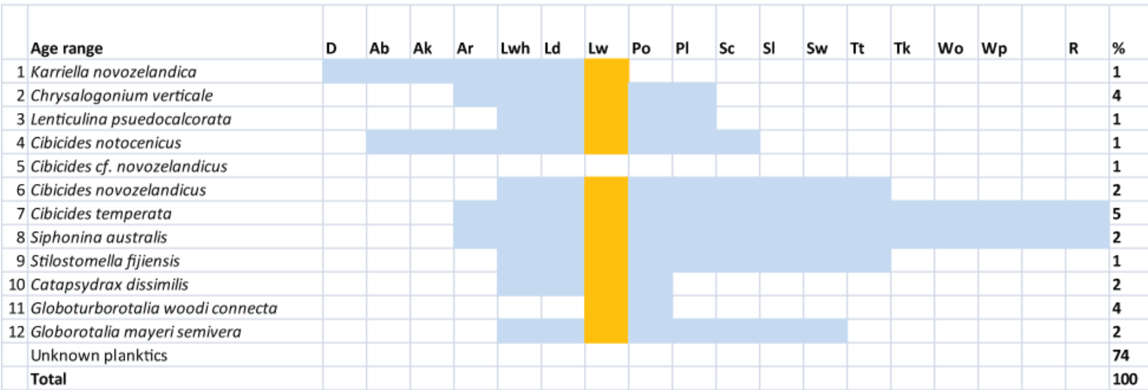


Figure 3.5 Foraminifera in sample 28 (from Gore Bay Quarry), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

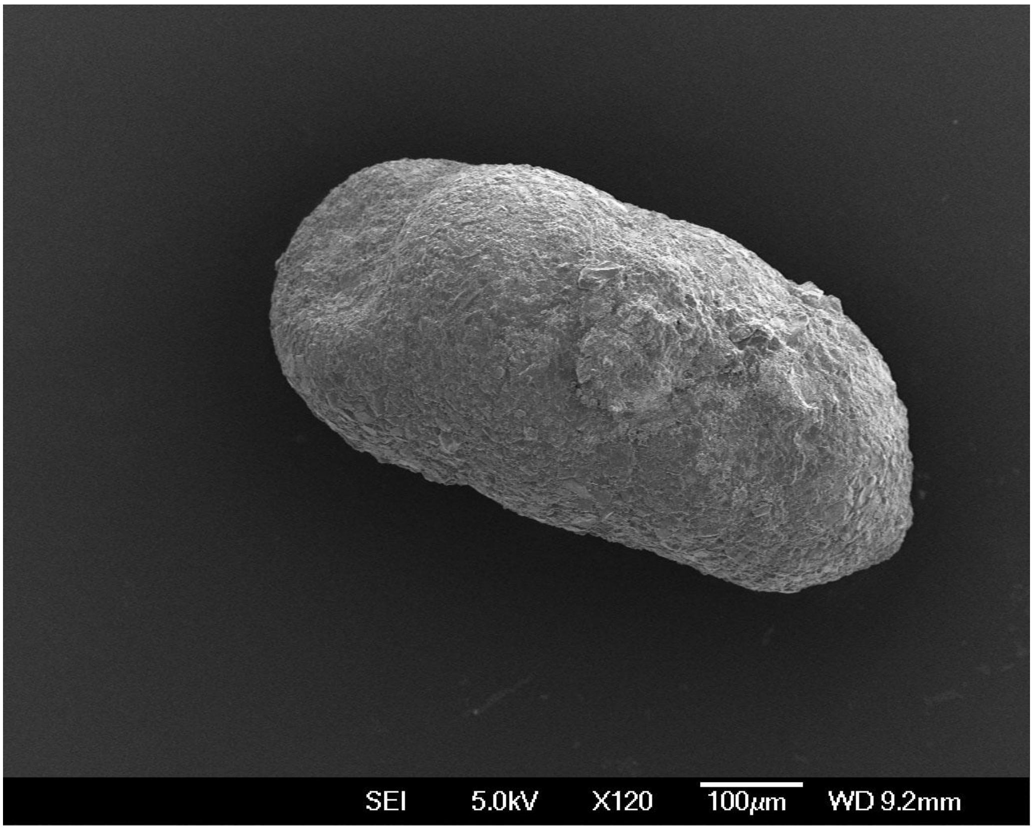


Figure 3.6 SEM photograph of *Karreriella novozealandica* from sample 28. Magnification is 100x.

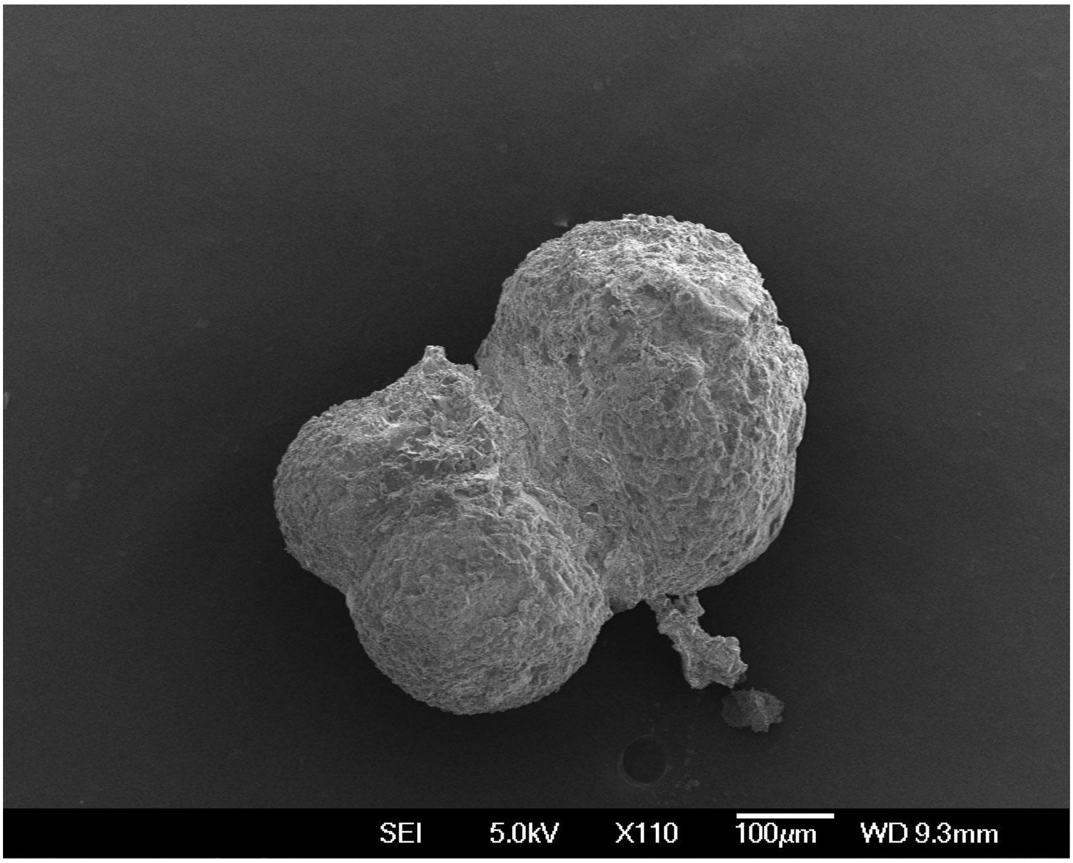


Figure 3.7 SEM photograph of *Globoturborotalia woodi connecta* from sample 28. The magnification is 110x.

Oaro

<u>Sample JI 6</u>

Planktics: 90% Age: Waitakian-Otaian (25.2 – 18.7Ma)

Diversity indices: S= 10 D= 0.759 E= 0.192 H= 0.654 (1.92) D= 0.241

The sample, the lowest taken at Oaro, was collected 1.75m above the base of the Motunau Group from a bioturbated horizon with wispy silt layers within the Planktic Foraminifera lithofacies (Fig. 2.16). The assemblage is 90% planktic, twenty percentage points higher than the equivalent basal Motunau assemblages at Gore Bay (JI1 and 2). Preservation quality was an issue which led to difficulties identifying the planktic specimens. The assemblage contained 7 benthic species and included one reworked specimen (*Nuttalides carinotruempyi*). All benthic specimens were identified to the species level; the most common was *Cibicides temperata* with 3% of the sample. Three planktic specimens were identified, all as *Globoturborotalia woodi connecta.*

The age of this sample is Waitakian- Otaian. The upper age limit is constrained by *Globoturborotalia woodi connecta* and the lower age limit is constrained by both *G. woodi connecta* and *Rectobolivina maoriella.*

	Age range	D	Ab	Ak	Ar	Lwh	Ld	Lw	Po	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp		R	%
1	*Anomalinoides parvumbilia*																			**1**
2	*Cibicides novozelandicus*																			**1**
3	*Cibicides temperata*																			**3**
4	*Gyroidinoides zelandicus*																			**1**
5	*Notorotalia sp.*																			**1**
6	*Rectobolivina maoriella*																			**1**
7	*Stilostomella pomuligera*																			**1**
8	*Globigerina woodi connecta*																			**3**
9	*Nuttalides carinotruempyi* -reworked																			**1**
	Unknown planktics																			**87**
	Total																			**100**

Figure 3.8 Foraminifera in sample 6 (from Oaro), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

<u>Sample JI 8</u>

Planktics: 66% Age: Waitakian-Otaian (25.2 – 18.7Ma)

Diversity indices: S= 15 D= 0.363 E= 0.334 H= 1.61 (5.00) D= 0.637

This sample was collected 7m above the Marshall Paraconformity from the Planktic Foraminifera Packstone lithofacies in the lower Motunau Group. The assemblage has decreased in planktic percentage from the previous sample (JI6), from 90% to 66%. The assemblage is similar to JI6 in terms of which species are present, except the number of benthic species has increased to 11 from 7. The genus *Cibicides* (C. *novozelandicus, C.perforatus and C. temperata*) makes up 13% of the sample and is the main benthic constituent. Of the 34 benthic specimens, 18 were identified to the species level, 4 to the genus level and 12 remained unidentifiable. In total, 9 species (among 8 genera) and 2 additional genera were identified. Preservation of planktics was poor and only eight were identified: one as *Globoturborotalia woodi connecta* and seven as possible *Globoturborotalia woodi,* which were not included when considering the age range due to uncertainty.

While there is still a large group of indentified planktics, it is smaller than the previous samples, resulting in a potentially more accurate statistics. Diversity is low (H= 1.61), as is evenness.

The age of this sample has be constrained to the same age range as the sample below it (JI6), Waitakian-Otaian. This is construed by the range of both *Globoturborotalia woodi connecta* and *Haeuslerella hectori*, and by the lower limit of *Rectobolivina rerensis.*

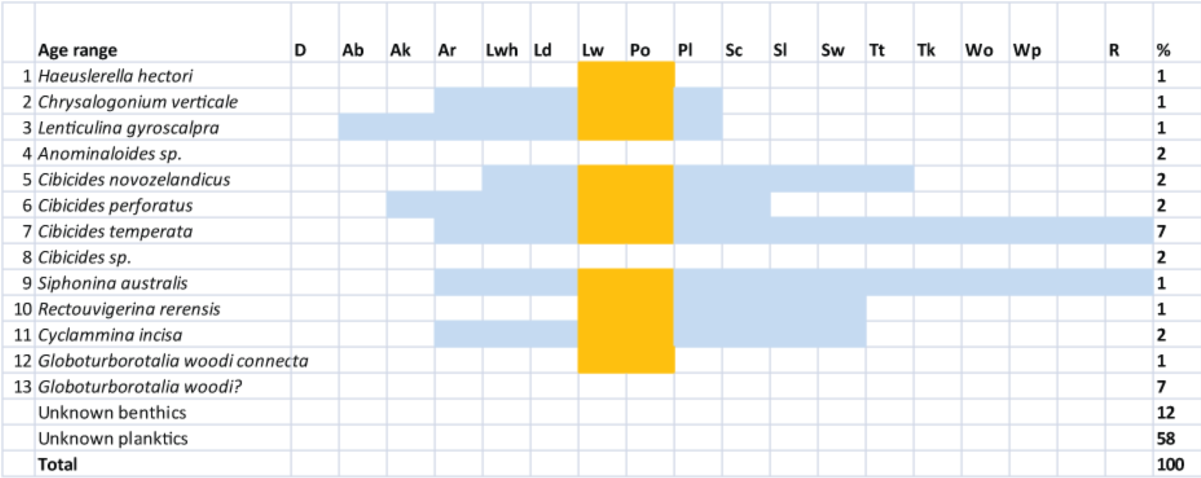


Figure 3.9 Foraminifera in sample 8 (from Oaro), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

Mendip Hills

<u>Sample JI 25</u>

Planktics: 57% Age: Waitakian (25.2 – 21.7Ma)

Diversity indices: S= 18 D= 0.342 E= 0.334 H= 1.794 (6.01) D= 0.658

This sample was located in the Muddy Sandstone lithofacies in the Mendip region (Fig 2.1). The sample was collected in a 2m bed of calcareous siltstone, situated an estimated 7m above the base of the Motunau Group (Fig. 2.19). The sample is 57% planktic, 43% benthic and contains 15 benthic species. Of the 43 benthic specimens, 35 were identified to the species level; the remainder were identified to the genus level. With three species (*C. notocenicus, C.novozelandicus*, *C. temperata*) and 16% of the sample, *Cibicides* was the most prominent genus. Another major group in the sample was infaunals (*Karreriella*, *Chrysalogonium, Dentalina*, *Lagenonodosaria and Stilostomella*), which consisted of 9 species and 15% of the sample.

As with the preceding sample, JI8, the number of unidentified planktics is lower than samples analyzed previously, resulting in less-skewed statistical results. Evenness is low, slightly lower than in JI8, however the effective diversity is 1.2x higher.

The age of the this sample was constrained to Waitakian. The lower limit is given by *Bolivina subcompacta*, and the upper limit by *Karreriella novozelandica,* and *Lenticulina pusilla*.

	Age range	D	Ab	Ak	Ar	Lwh	Ld	Lw	Po	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp		R	%
1	*Karreriella novozelandica*																			2
2	*Textularia pseudomiozea*																			1
3	*Chrysalogonium verticale*																			1
4	*Lagenonodosaria hirsuta*																			1
5	*Lenticulina pusilla*																			1
6	*Anomalinoides parvumbilius*																			3
7	*Cibicides notocenicus*																			2
8	*Cibicides novozelandicus*																			1
9	*Cibicides temperata*																			6
10	*Cibicides sp.*																			7
11	*Gyroidinoides zelandicus*																			3
12	*Siphonina australis*																			5
13	*Bolivina subcompacta*																			1
14	*Stilostomella verneuilii*																			1
15	*Stilostomella sp*																			1
16	*Dentalina soluta*																			3
17	*Dentalina substrigata*																			4
	Unknown planktics																			57
	Total																			**100**

Figure 3.10 Foraminifera in sample 25 (from Mendip Hills), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

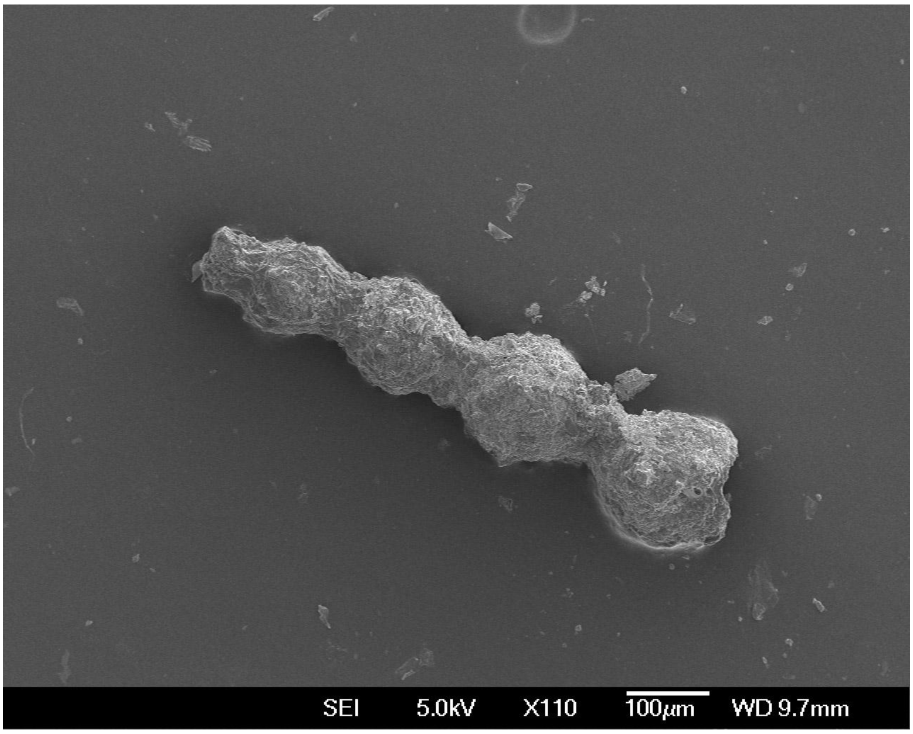


Figure 3.11 SEM photograph of *Dentalina soluta* from sample 25. Magnification is 100x.

Whale's Back

<u>Sample JI 44</u>

Planktics: 5%   Age: Otaian-Altonian boundary (18.7Ma)

Diversity indices: S= 17   D= 0.363   E= 0.335   H= 1.738 (5.69)   D= 0.637

This sample was collected from the Calcareous Sandstone lithofacies along a road cut in the Whale's Back region (Fig. 2.1, Fig. 2.20). The sampled horizon was composed of calcareous fine sand and included glauconite-rich burrows as well as phosphatised nodules and brachiopods. The sample is 5% planktic, and is characterized by an abundance of *Stilostomella pomuligera* (Fig. 3.13), which makes up 59% of the sample. All but 4 of the specimens were identified to the species level; the remaining 4 were identified to the genus level.

This sample is contemporaneous with the previous one from Wandle River. Statistics show some differences between the two sites: The number of species is the same between the two (17), however the dominance is higher and evenness lower in this sample. The biggest difference is diversity indices, as this sample is 1.23x lower (eH= 7.03) than at Wandle River. The age of the sample can be restricted to the Otaian-Altonian boundary. This date is given by the overlap of *Globoturborotalia woodi connecta* with *Globigerinoides trilobus* and *Textularia miozea*.

	Age range	D	Ab	Ak	Ar	Lwh	Ld	Lw	Po	Po-Pl	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp		R	%
1	*Bigerna sp.*																				1
2	*Textularia miozea*																				3
3	*Dentalina substrigata*																				1
4	*Lenticulina sp.*																				2
5	*Anomalinoides parvumbilius*																				1
6	*Cibicides notocenicus*																				2
7	*Cibicides novozelandicus*																				2
8	*Cibicides temperata*																				6
9	*Cibicides sp.*																				3
10	*Bolivina targetensis*																				4
11	*Bulimina miolaevis*																				2
12	*Stilostomella awamoana*																				6
13	*Stilostomella pomuligera*																				59
14	*Trifarina parva*																				1
15	*Ammobaculites calcareus*																				2
16	*Globoturborotalia woodi connecta*																				4
17	*Globigerinoides trilobus*																				1
	Total																				100

Figure 3.12 Foraminifera in sample 44 (from Whale's Back), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

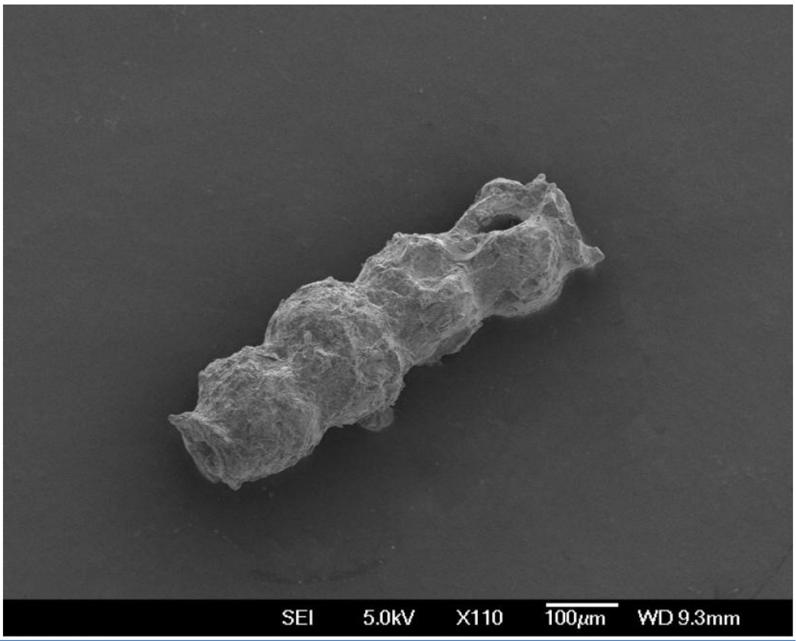


Figure 3.13 SEM photograph of *Stilostomella pomuligera* from sample 44. This image demonstrates the poor preservation quality typical of many samples in this study. The test walls of this species should be clear and glossy. Magnification is 110x.

Sample JI 49

Planktics: 2% Age: Duntroonian (27.3-25.2Ma)

Diversity indices: S= 20 D= 0.153 E= 0.528 H= 2.357 (10.56) D= 0.847

This sample is unique to this study, as it is the only volcaniclastic limestone sample collected. It was located within an outcrop of the Cookson Volcanics in the Whale's Back area, in the Calcareous Volcaniclastic Sandstone lithofacies (Fig. 2.20). The foraminifera are glauconitized, resulting in well preserved specimens. The sample is 2% planktic, with planktic species including *Globorotaloides testarugosus* and an apparently reworked specimen of *Globigerina linaperta*. The main constituents are *Cibicides perforatus* (32%) and *Elphidium crispum crispum* (16%). There are 4 species of *Cibicides* in this assemblage, including *C. notocenicus, C. perforatus, C. temperata* and C. *vortex*, which make up 46% of the entire sample. In total, 15 species were identified.

The sample includes at least one important palaeoecological indicator, *Bolivinella rugosa* (2%) (Fig. 3.14a). According to Hayward (1982), *B. rugosa* is a rare component in foraminiferal fauna, never constituting more than 1-3% of the assemblage. It is often found in fauna which are dominated by genera such as *Cibicides, Bolivina, Quinqueloculina, Elphidium* and *Notorotalia*, an assemblage characteristic of modern inner shelf sandy environments (Hayward, 1982). This characterization is consistent with that seen in this sample, which is dominated by *Cibicides, Elphidium* (Fig. 3.14b) and *Notorotalia* (Fig 3.16d).

Diversity in this sample is very high (H=10.56), one of the highest values among all the samples. Evenness is medium (E= 0.53) and dominance is high (D= 0.15).

The age of this sample is Duntroonian, the oldest sample collected in this study. The lower age is constrained by *Bolivinella rugosa* and *Notorotalia spinosa*, and the upper by *Eoepondella zealandica* and *Globorotaloides testarugosus.*

	Age range	D	Ab	Ak	Ar	L.Lwh	U.Lwh	Ld	Lw	Po	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp		R	%
1	*Anominaloides fasciatus*																				2
2	*Cibicides notocenicus*																				8
3	*Cibicides perforatus*																				32
4	*Cibicides temperata*																				2
5	*Cibicides vortex*																				3
6	*Cibicides sp.*																				1
7	*Elphidium crispum crispum*																				16
8	*Eoeponidella zealandica*																				4
9	*Heronallenia wilsoni*																				3
10	*Notorotalia spinosa*																				9
11	*Bolivinella rugosa*																				2
12	*Buliminoides sp.*																				2
13	*Epistominella sp.*																				3
14	*Hoeglundina sp.*																				1
15	*Gaudryina proreussi* - reworked																				2
16	*Spirillina sp.*																				1
17	*Globorotaloides testarugosus*																				1
	Unknown benthics																				6
	Unknown planktics																				1
	Unknown planktics, reworked																				1
	Total																				100

Figure 3.13 Foraminifera in sample 49 (from Whale's Back), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

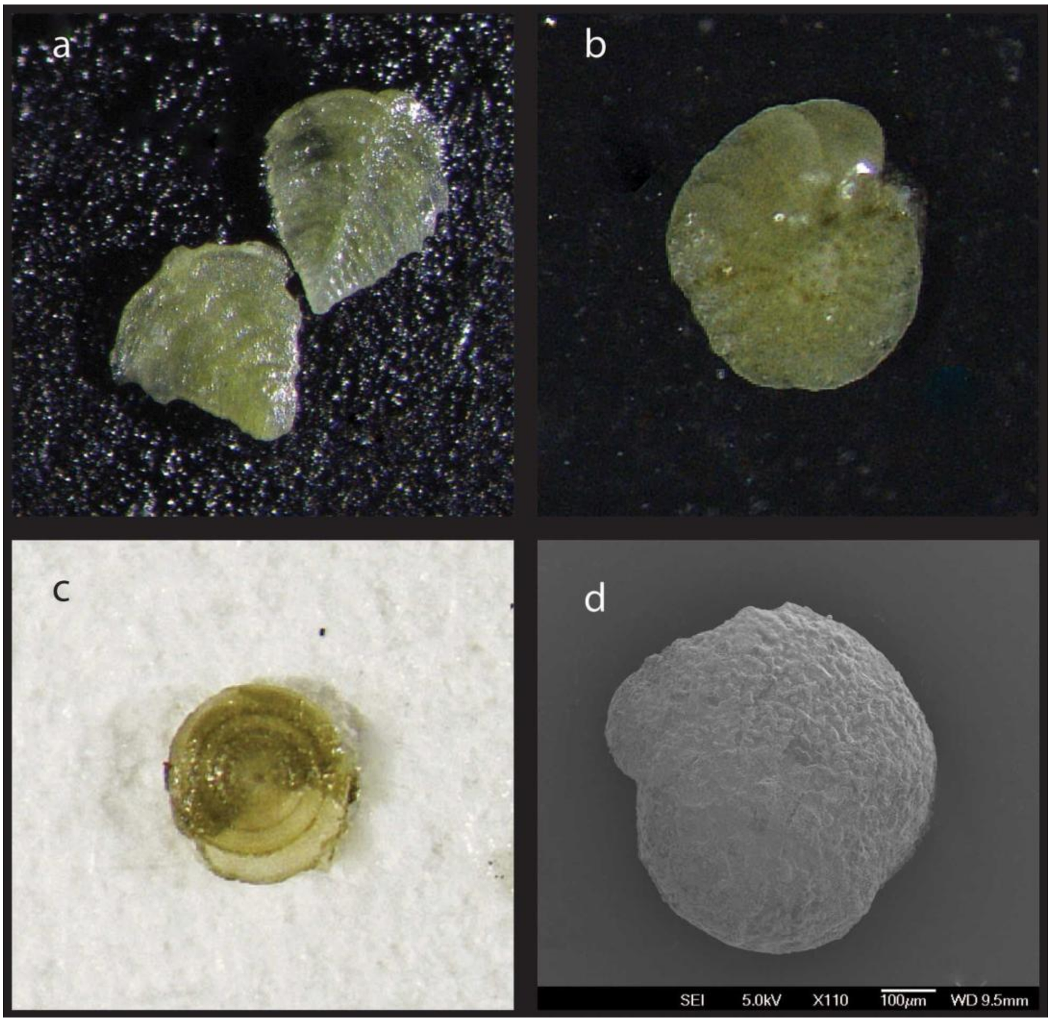


Figure 3.14 Photographs (a-c) and SEM photograph (d) of various foraminifera specimens from sample 49. Magnification is 110x. a) *Bolivinella rugosa* b) *Elphidium crispum crispum* c) *Spirillina sp.* d) *Notorotalia spinosa*.

Little Lottery River

Sample JI 56

The foraminifera were not identified in this sample, however it contained an abundance of ostracods, which were identified by Dr. Kerry Swanson in order to provide extra evidence when determining palaeoenvironments. Five analyzed specimens were determined to be various species belonging to the genera *Chytherella* (4), and *Bisulcocythere* (1). Macrofossils were present, and were identified as a bivalve of the genus *Cucullaea* and a Turritellid gastropod, possibly of the genus *Maoricolpus.*

Figure 3.15 Photograph of macrofossils observed at sample site JI56. Bivalve Cucullaea (a) and gastropod (b)

Sample JI 52

Planktics: 6% Age: Tongaporutuan (11.01-7.2Ma)

Diversity indices: S= 15 D= 0.128 E= 0.639 H= 2.26 (9.58) D= 0.872

This sample was collected from the Calcareous Sandstone lithofacies in the Waima Formation along the Little Lottery River (Fig 2.1), taken from halfway up the measured section (Fig. 2.21). The horizon from which it was collected contained very fine grained, well indurated, calcareous concretions. The sample is 6% planktic. Of the 94 benthic specimens, 19 were not identified due to preservation quality, 3 were identified to the genus level and the remaining comprised 10 species. *Anomalinoides parvumbilia, Bolivinita pohana, Cibicides molestus* and *Oridorsalis umbonatus* were the main constituents of the sample, each with 11 specimens.

Despite the relatively large group of unidentified planktics (19), diversity indices remain high for this sample (H= 9.58), as is evenness (E= 0.64). Dominance is very low (D= 0.128).

This sample is Tongaporutuan in age, constrained by the age range of *Bolivinita pohana*. The lower age range is also restricted by *Cibicides neoperforatus* and *Uvigerina pliozea* (Fig 3.18), while the upper is also restricted by *Rectobolivina parvula*.

	Age range	D	Ab	Ak	Ar	Lwh	Ld	Lw	Po	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp	Wn		R	%
1	*Quinqueloculina sp*																				1
2	*Anomalinoides parvumbilia*																				11
3	*Cibicides molestus*																				12
4	*Cibicides neoperforatus*																				2
5	*Cibicides temperata*																				2
6	*Cibicides sp.*																				2
7	*Nonionella flemingi?*																				1
8	*Oridorsalis umbonatus*																				11
9	*Pullenia buliminoides*																				1
10	*Bolivinita pohana*																				20
11	*Rectobolivina parvula*																				1
12	*Uvigerina pliozea*																				2
13	*Hoeglundia elegans*																				9
14	*Globorotalid sp.*																				6
	Unknown benthics																				19
	Total																				**100**

Figure 3.16 Foraminifera in sample 52 (from Little Lottery River), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

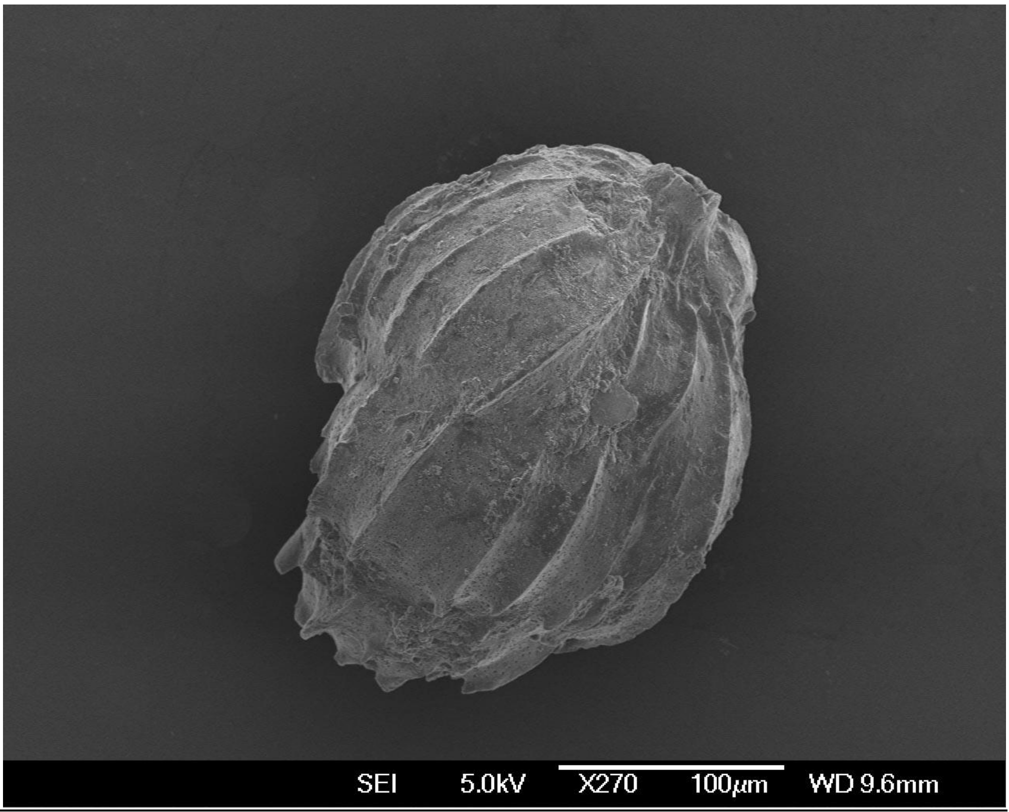


Figure 3.17 SEM photograph of *Uvigerina pliozea* from sample 52. Magnification is 270x.

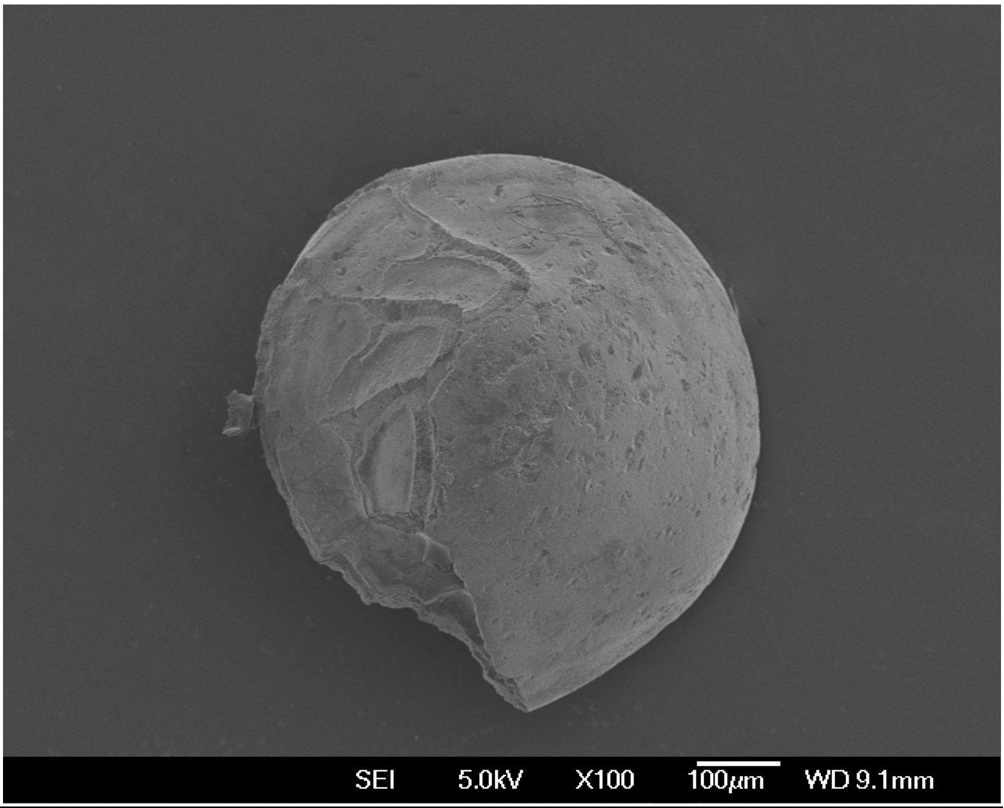


Figure 3.18 SEM photograph of *Hoeglundus elegans* from sample 52. Magnification is 100x.

Sample JI 55

Planktics: 2%   Age: Tongaporutuan (11.01-7.2Ma)

Diversity indices: S= 22 D= 0.141 E= 0.528 H= 2.452 (11.61) D= 0.859

This sample was collected from the Little Lottery River outcrop, 4m above sample JI52. The horizon was a poorly indurated, silty sandstone horizon in the Calcareous Sandstone lithofacies (Fig. 2.21). The assemblage is only 2% planktic, a substantial drop from 15% in JI52. There is a higher number of species in this sample than JI52, with 18 species and an additional two genera not identified to the species level. This is the highest benthic diversity among the samples collected. *Anomalinoides albatrossi* and *Bolivinita pohana* remained the dominant species in the assemblage, with 22% and 27% respectively; these number are double their abundance in JI52. The other dominant species in JI52 decreased in abundance in this sample; *Cibicides molestus* dropped from 12% to 6%, *Oridorsalis umbonatus* dropped from 11% to 3%.

Statistical analysis confirms the diversity has increased from the sample stratigraphically below this one. This sample is has an effective diversity 1.2x higher than JI52. Evenness has decreased, and dominance increased.

The age of the sample remains Tongaporutuan, constrained by *Bolivinita pohana, Cibicides neoperforatus, Cibicides novozelandicus,* and *Textularia miozea (*Fig. 3.20a-c).

	Age range	D	Ab	Ak	Ar	Lwh	Ld	Lw	Po	Po-Pl	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp		R	%
1	*Textularia miozea*																				2
2	*Amphicoryna hirsuta*																				1
3	*Amphicoryna sublineata?*																				5
4	Nodosarid sp.																				1
5	*Anomalinoides parvumbilia*																				22
6	*Cibicides molestus*																				6
7	*Cibicides neoperforatus*																				2
8	*Cibicides novozelandicus*																				1
9	*Cibicides vortex*																				1
10	*Gavelenopsis sp.*																				1
11	*Notorotalia taranaki*																				8
12	*Oridorsalis umbonatus*																				3
13	*Bolivina albatrossi*																				3
14	*Bolivina cf. barnwelli*																				3
15	*Bolivina cf. subcompacta*																				2
16	*Bolvinita pohana*																				27
17	*Stilstomella pomuligera*																				3
18	*Uvigerina pliozea*																				2
19	*Globocassidulina subglobosa*																				2
20	*Hoegludina elegans*																				2
21	*Globoturborotalia woodi connecta?*																				2
	Unknown benthics																				1
	Total																				**100**

Figure 3.19 Foraminifera in sample 55 (from Little Lottery River), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

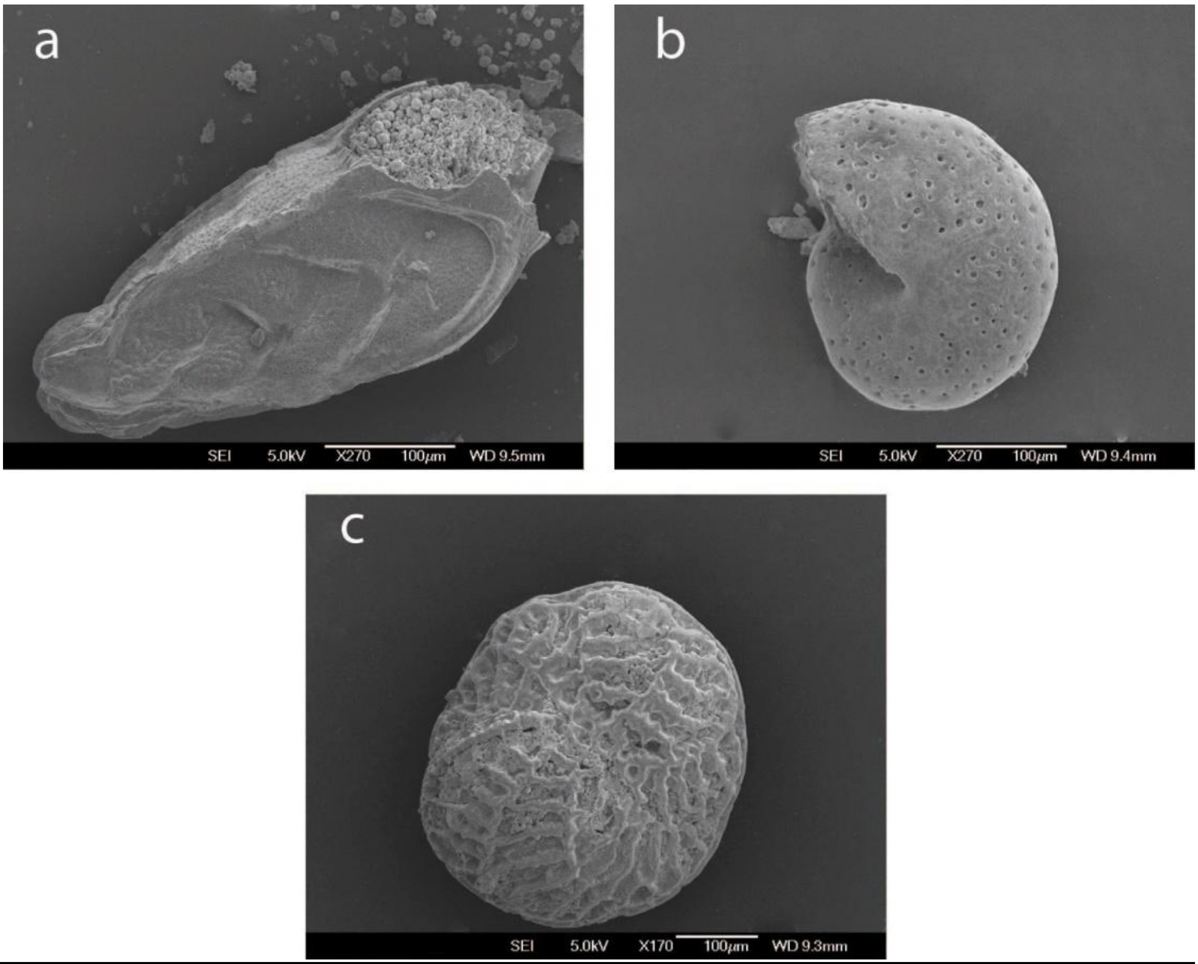


Figure 3.20 SEM photographs from sample 55. Magnification is 100x. a) *Bolivinta pohana* b) *Anominaloides parvumbilium* c) *Notorotalia spinosa*.. These specimens, the youngest in the study, show much better preservation quality than their predecessors.

<u>Samples JI 54</u>

Planktics: N/A   Age: Tongaporutuan (11.01-7.2Ma)

Diversity indices: N/A

This sample was collected from the Little Lottery River outcrop, approximately 7m above sample JI 55 in the Calcareous Sandstone lithofacies (Fig. 2.21). It is the stratigraphically highest sample collected for this project. Due to very low proportion of foraminifera in the sample, only 20 specimens were collected. As a result, the planktic: benthic ratio is not statistically significant and therefore has not been included. The species observed are the same as in sample JI55; *Cibicides neoperforatus* is particularly abundant, with 7 specimens (35%). All other species identified contain 1-2 specimens. Three specimens, 1 benthic, 1 infaunal and 1 planktic, were not identified due to preservation quality. Diversity indices were not run, due to the lack of specimens in the sample.

The age of the sample is the same as the other two Little Lottery River samples, Tongaporutuan. This age is given by *Bolivinita pohana* and *Globorotalia mayeri mayeri*.

	Age range	D	Ab	Ak	Ar	Lwh	Ld	Lw	Po	Pl	Sc	Sl	Sw	Tt	Tk	Wo	Wp		R	%
1	*Spiroloculina henbesti?*																			1
2	*Anomalinoides parvumbilia*																			1
3	*Cibicides molestus*																			2
4	*Cibicides neoperforatus*																			7
5	*Bolivinita pohana*																			2
6	*Stilstomella pomuligera*																			1
7	*Hoeglundia elegans*																			2
8	*Globorotalia mayeri mayeri*																			1
	Unknown benthic													^earliest Tt						1
	Unknown infaunal																			1
	Unknown planktic																			1
	Total																			**20**

Figure 3.21 Foraminifera in sample 55 (from Little Lottery River), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

Wandle River

Sample JI 59

Planktics: 2% Age: Earliest Altonian (~18.7Ma)

Diversity indices: S= 17 D= 0.281 E= 0.414 H= 1.95 (7.03) D= 0.719

This sample was collected from the Calcareous Sandstone lithofacies which outcrops along the Wandle River (Fig 2.1). The horizon of well indurated fine sandstone was located an unknown distance above the base of the Motunau Group (Fig. 2.22). The sample is composed of nearly all benthics, with only 2% planktics. All but 6 of the specimens were identified to the species level, the remainder being identified to the genus level. In total, the sample is composed of 14 benthic and 2 planktic species. The sample is made up predominantly of Buliminida and *Cibicides*, with 5 species of *Bolivina* and *Bulimina* and 3 species of *Cibicides.* The sample is dominated by *Cibicides temperata* (51%); specimens of the order Buliminida make up 13% and *Cibicides molestus* and *C. perforatus* makes up a further 11%.

Statistical analysis is very useful for this sample, as all specimens were identified. This sample has 17 groups in total, high dominance, low evenness and medium diversity. The high dominance is due to the large percentage of *Cibicides temperate*,

The age of the sample is earliest Altonian. The lower limit is given by *Bolivina zedirecta*, and the upper limit by *Bulimina pupula* and *Globoturborotalia woodi connecta.*

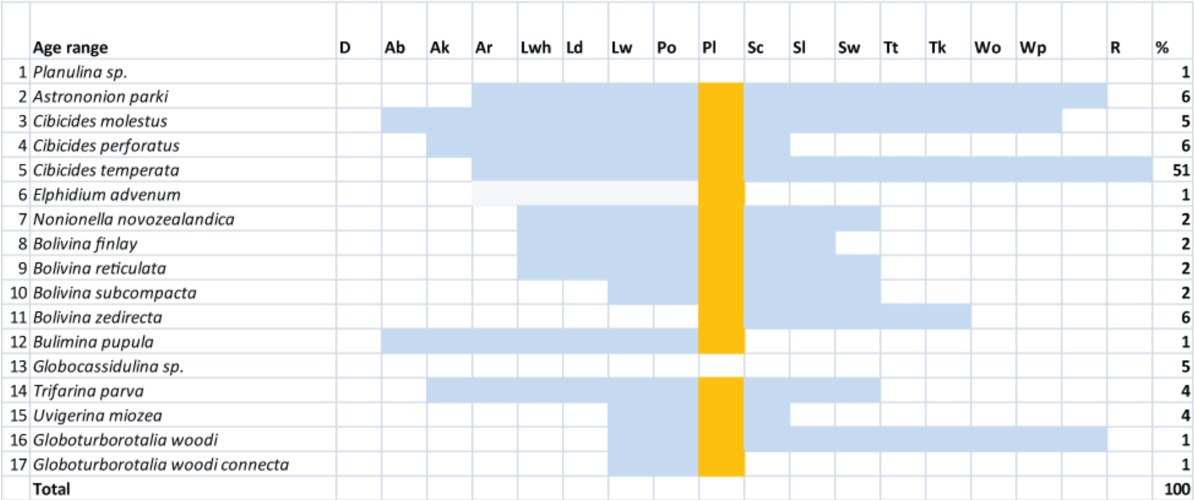


Figure 3.22 Foraminifera in sample 59 (from Wandle River), and abundance and biostratigraphic range of each taxon. Raw data is shown in Appendix B.

Summary

For this project, fourteen samples from within six of the seven lithofacies were found to have enough foraminifera specimens to provide age and palaeoenvironment data. In some samples, the preservation quality of the specimens was extremely poor, resulting in a low number of identifications and broad age ranges. Most ages, however, were well constrained and overall they range from the Duntroonian to the Tongaporutuan. Diversity indices, such as dominance, evenness and Shannon-Weiner, were run on the data where possible, though they do not show much of a trend over time (see Figs. 3.24-25).

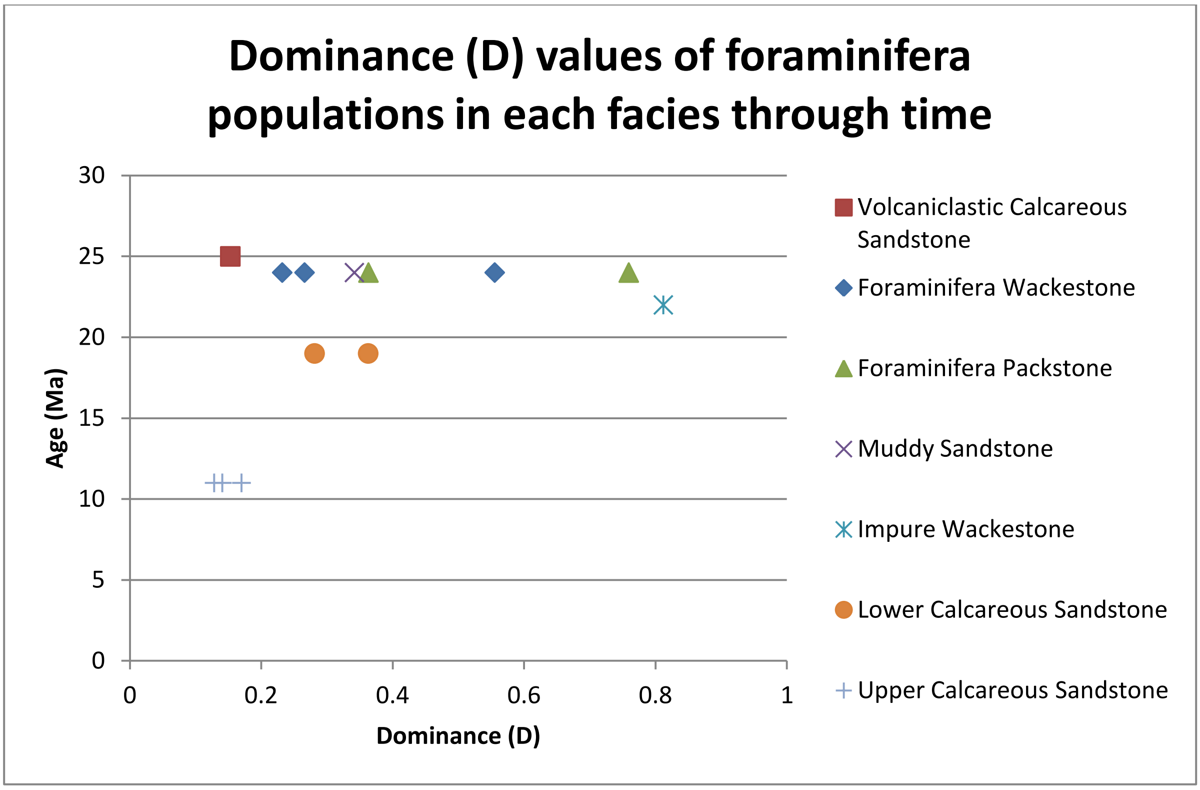


Figure 3.21 Scatter plot depicting the various dominance values (D) of each foraminifera population. Populations are grouped by lithofacies throughout time. No trend in the data is apparent before 20Ma; after 20Ma, the dominance on the Calcareous Sandstone lithofacies is shown to decrease through time.

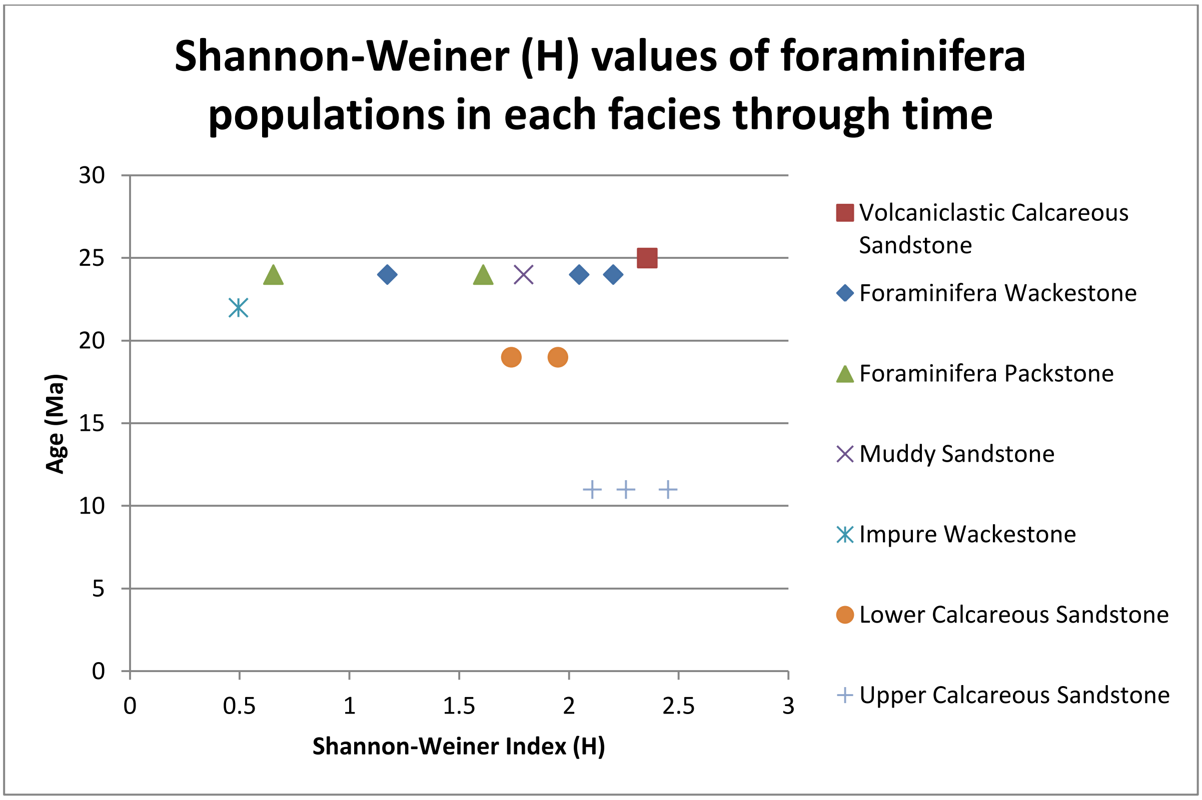


Figure 3.22 Scatter plot depicting the various Shannon-Weiner index values (H) of each foraminifera population. Populations are grouped by lithofacies throughout time. No trend in the data is apparent before 20Ma; after 20Ma, the value of H of the Calcareous Sandstone lithofacies increases, indicating higher diversity.

4 GEOCHEMISTRY

4.1 Introduction

Analysis of the stable isotopes of carbon and oxygen is widely used by researchers in various fields, especially in the study of palaeoclimatology. The oxygen isotope in a carbonate may reflect the composition, salinity and temperature of the seawater at the time of deposition; in palaeoceanographic reconstructions, $\delta^{18}O$ in normal marine conditions reflects ice formation or melt, and therefore sea level changes (Kump and Arthur, 1999; Zachos et al., 2001). Carbon isotopes in carbonates may reflect the source of the carbonate, such as sea water, microbial oxidation of organic materials or marine shell dissolution (Nelson and Smith, 1996); in palaeoceanographic reconstructions, $\delta^{13}C$ may reflect productivity levels in the ocean at the time of deposition. The isotope values can however be altered during diagenesis by the composition of pore fluids and values measured will not be representative of original conditions (Veizer et al., 1999).

Whole-rock geochemical analysis, to determine ^{18}O and ^{13}C values, was done on samples from Gore Bay, Kaikoura and Cribb Creek to provide further evidence for ocean conditions during the mid Oligocene to early Miocene. In these deep-water carbonates, seafloor cements are absent and in many samples burial cements are sparse. The source of carbonate therefore mostly from bioclasts which are assumed to be in isotopic equilibrium with seawater. The propensity of oxygen isotopes to be altered during diagenesis means that these results must be viewed with caution, however the carbon isotope results are less likely to be altered during burial (Banner and Hanson, 1990) and may give a closer approximation of original seawater composition. This is evidenced by the results from Cribb Creek (which were not analyzed, see discussion below) and is possibly also seen in the results from the other two locations- as there are many discrepancies between some data points from Kaikoura and Gore Bay.

However, the data set may still give some basic insight into sea level changes and oceanic productivity levels.

4.2 Methods

Collection of samples

The locations chosen for geochemical work were Gore Bay, Kaikoura and Cribb Creek, as these locations include a complete section from the top of the Amuri Limestone and records unconformity correlated with the Marshall Paraconformity. Samples were collected at 1m intervals, starting 5m below the Marshall Paraconformity, through to 10m above the paraconformity, after which sampling continued at 10m intervals to the top of the section. The samples collected were from unweathered surfaces to ensure accurate results. Samples for thin sections were collected at the same intervals for petrographic analysis. All samples are detailed in Appendix C.

Whole-rock geochemical analysis

Whole-rock geochemical analysis was performed using the technique described by Horton et al. (2004). The analysis was carried out at the Stable Isotopes Lab at the University of Canterbury, using a Continuous Flow Isotope Ratio Mass Spectrometer. The samples were run under the supervision of Dr. Travis Horton. Dependant on the amount of carbonate present in the sample, ~150-300µg of powder was extracted from the limestones using a Dremel tool. The powder was sealed in a reaction vessel, flushed with helium, raised to a temperature of 70°C and reacted with 100% phosphoric acid. The resulting head space of carbon dioxide was sampled using with a Finnigan Gas-Bench, and isotopic ratios were measured on a Finnigan Delta V Plus IR mass spectrometer.

4.3 Geochemistry Results

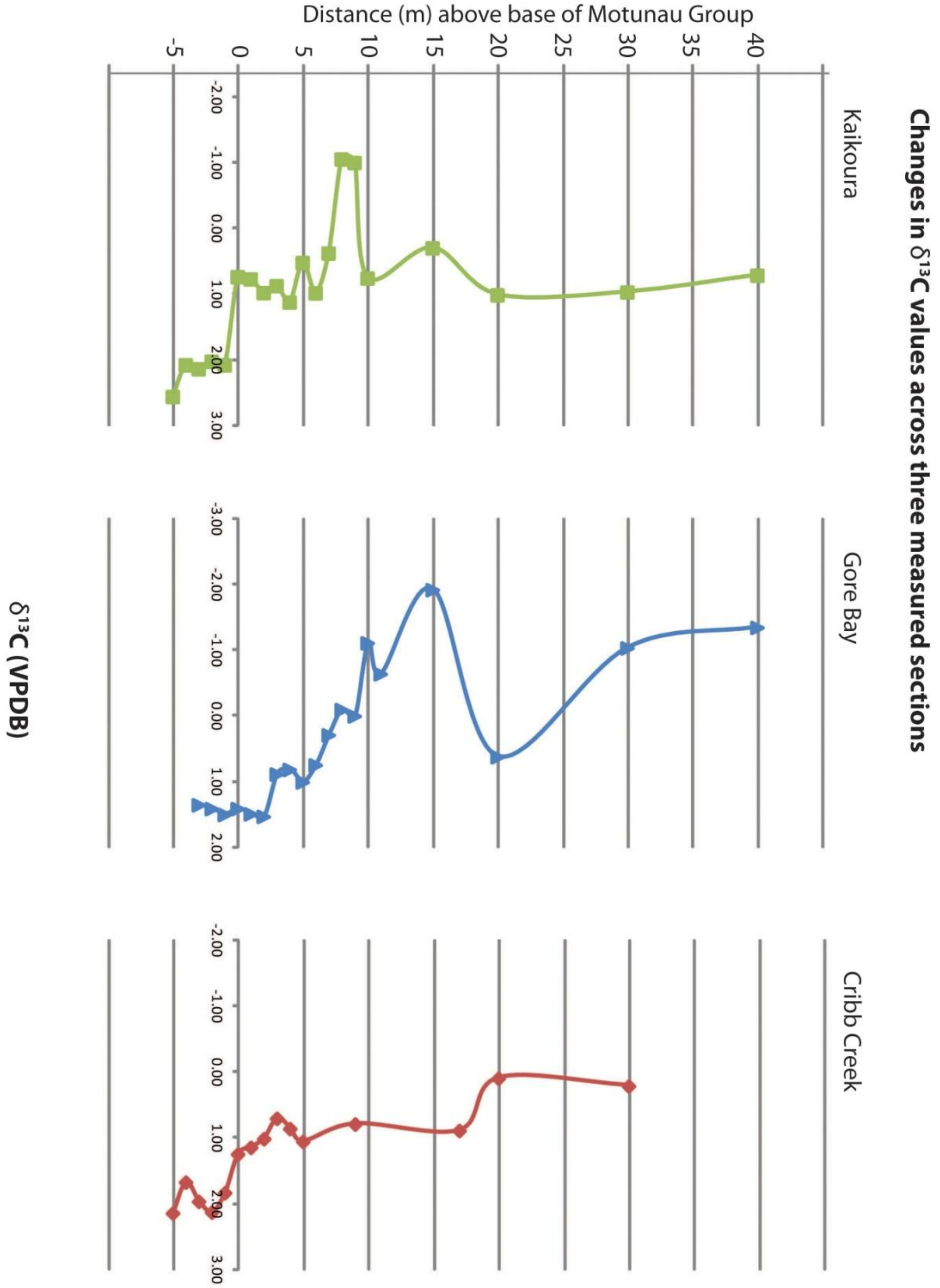


Figure 4.1 Changes in $\delta^{18}O$ values through the measured sections of Cribb Creek (red), Gore Bay (blue) and Kaikoura (green).0m is immediately below the Marshall Paraconformity. The vertical axis is in metres, so equivalent points across the three sections are not necessarily of the same age.

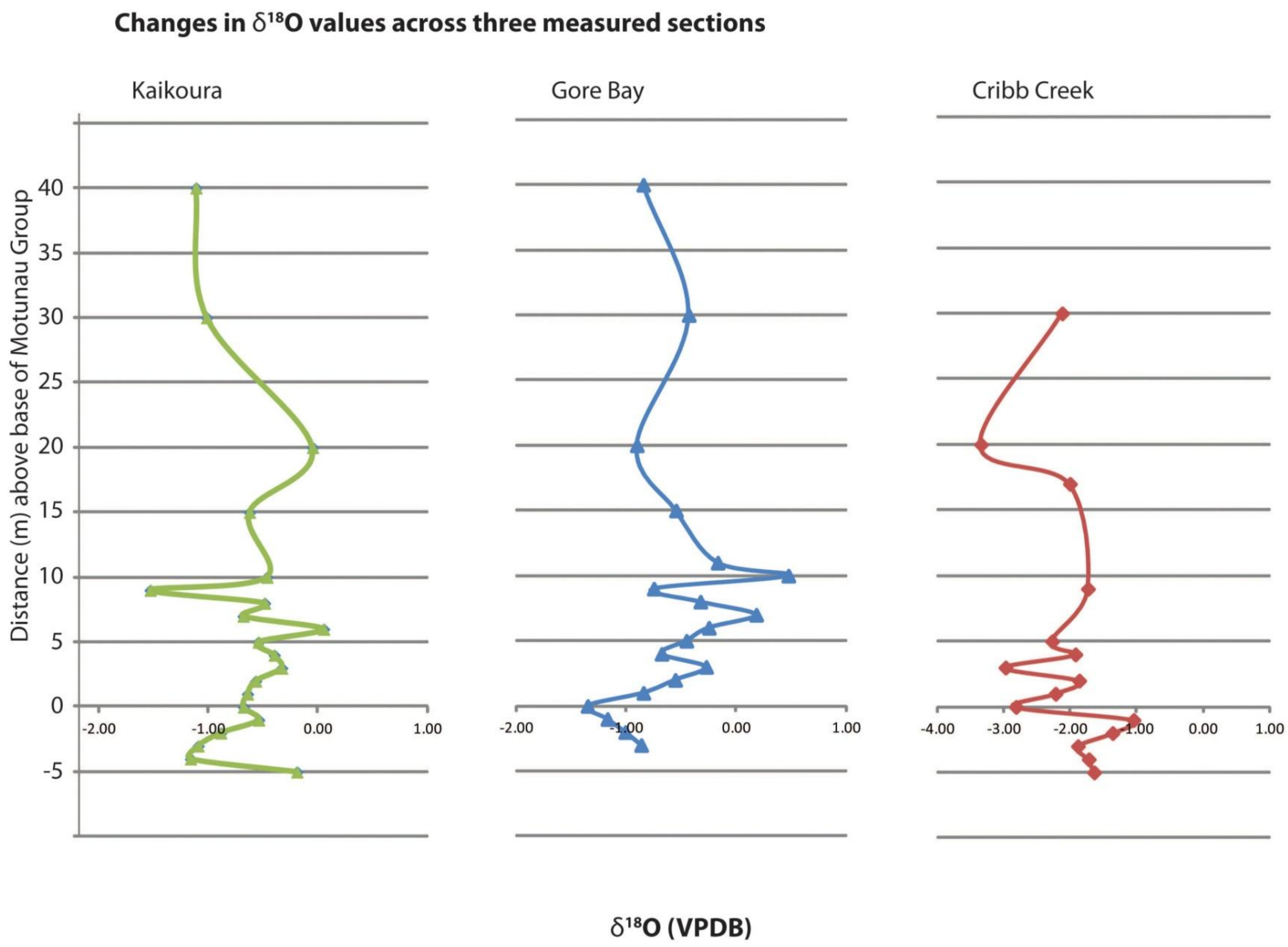


Figure 4.2 Changes in $\delta^{18}O$ values through the measured sections of Cribb Creek (red), Gore Bay (blue) and Kaikoura (green).0m is immediately below the Marshall Paraconformity. The vertical axis is in metres, so equivalent points across the three sections are not necessarily of the same age.

Oxygen

Oxygen values beginning at 5m below the Marshall Paraconformity range from -0.25 – -1‰O. At all locations, there is a negative excursion by a value of ~ -0.5‰ O from 4-2m, before values return back to where they started. Unexpectedly, there is no sharp excursion in oxygen values over the Paraconformity; instead, the trend is a gradual positive shift which continues to 6m above the Paraconformity, where the values reach +0.2‰O. After this peak, the values progressively return to -0.5‰ O. The data points between the three locations are often random and do not mirror one another. This disparity between all the locations is a possible indicator that the oxygen values are recording alteration rather than the original value.

A second issue with the oxygen isotope data is that it does not reflect the sedimentary data. The one distinguishable trend seen in the oxygen data is a steady, post- Marshall Paraconformity enrichment in $\delta^{18}O$ at Gore Bay. If linked to sea ice volume and sea level, this should be indicative of a sea level fall due to ice growth and subsequent removal of O^{16} from sea water, a scenario which is not supported by the sedimentary data, as discussed in Chapters 2 and 3. As a result of this disparity, it is assumed the oxygen values do not reflect the original sea water composition, and must have been altered by diagenesis and therefore are ineffective. Diagenetic recrystallization of carbonates occurs in a system where carbonate minerals equilibrate with fluid $\delta^{18}O$ values at three times the magnitude lower water: rock ratio than the water: rock ratio which they equilibrate with $\delta^{13}C$ (Banner and Hanson, 1990). This difference results in oxygen isotope values being more readily altered during the diagenetic process than carbon isotopes (Veizer et al., 1999).

The oxygen values from the Cribb Creek samples (-1 – -3O‰) are, on average, 1-2‰ lower than those of Kaikoura (0 – -1.5O‰) and Gore Bay (-1.5 – -0.5O‰). This difference appears more strongly with the oxygen values than the carbon, suggesting the discrepancy is due to diagenesis of the Cribb Creek rocks. Accordingly, the Cribb Creek $\delta^{13}O$ results are not included in further discussion.

Carbon

The pre-Marshall Paraconformity carbon values vary from +2.0-2.5‰. There are no clear trends from any of the three locations beneath this boundary. The carbon values, like the oxygen values, do not show much significant shift over the measured sequence. The data shows the pre-Paraconformity values to be more enriched than the post-values, as the trend from the Marshall Paraconformity upwards to 9m is negative, going from +0.75‰ C (Kaikoura) and +1.5‰C (Gore Bay) to -1.0‰C (Kaikoura) and 0‰C (Gore Bay). After 9m, the trend could be considered to be slightly positive, however the values of Kaikoura and Gore Bay are so dissimilar that it would be impossible to draw any real conclusions.

The negative shift from 0m – 9m could be attributed to either a drop in biogenic productivity, or to an influx of new water from another location. The age associated with this 9m section, derived from the Gore Bay foraminifera assemblages, is Lower Waitakian, and is coincident with timing of cold water offshoots from the Antarctic Circumpolar Current affecting the eastern coastline of New Zealand (Fulthorpe et al., 1996). This data reflects the replenishment of deep-water due to the movement of Antarctic water northward along the eastern coast.

Summary

Due to apparent diagenetic alteration, the oxygen data can be discounted, both above and below the Paraconformity. The carbon data possibly reflects the influx of the ACC, as cold water off-shoots mixed with the waters offshore eastern New Zealand during the Waitakian. Both the carbon and oxygen data results are consistent with those of typical Cenozoic New Zealand limestones, (0-3C‰ and -1 - -4O‰) (Nelson and Smith, 1996).

5. DISCUSSION

5.1 Palaeoenvironments

Introduction

Combining the data outlined in Chapters 2-4, interpretations regarding aspects of the seven lithofacies' palaeoenvironments have be made. One of the main focuses of this project is to determine palaeobathymetry using foraminifera data. While individual species do not provide much information, assemblages as a whole can be very useful for determining palaeodepths. Planktic/benthic ratios, benthic species diversity and taxonomic composition of main benthic taxa are all conventional techniques used to estimate palaeodepth (Hayward, 2004). Planktic/benthic ratios have been applied to these types of studies since Grimsdale and Van Morkhoven's 1955 study, when the correlation between increased proportion of planktic foraminifera and distance from shore was first recognized. Despite the fairly systematic increase, there are some exceptions, such as in anoxic areas (Jorissen and de Stigter, 1990), which create an extremely wide data scatter (Grimsdale, 1955). As a result, the planktic/benthic ratio must be used in conjunction with other techniques to insure more accurate results. One way to improve on the accuracy of using planktic percentages was suggested by van der Zwaan et al (1990), where they found that disregarding infaunal specimens in an assemblage and simply using the planktic: epifaunal benthic ratio is much more accurate measure of water depth. In some cases, morphology can be used to give additional clues to environmental conditions; for instance, Mackensen et al. (1985) found epifaunal planoconvex forms to be typical of depths of 200-500m and 1600-2700m in the Norwegian Sea, while biconvex forms were indicative of depths of 1500-4000m. Some key biostratigraphic species, if found in high enough quantities in an assemblage, can give insight into specific environmental characteristics, such as *Globigerina bulloides*, which is a taxon associated with upwelling areas throughout the world (Murray, 1995).

However, all these techniques are merely helpful estimates which cannot be relied on for a complete palaeodepth reconstruction, due to the nature of foraminifera ecology and the ocean conditions in which they live. Assemblage distribution is influenced by both local and large scale factors, such as changes in oxygen levels, long term organic flux, grain size and water temperature, as well as possibly other factors which are not yet understood; depth alone is not the principal controlling factor of foraminifera distribution (Hornibrook et al., 1989; van der Zwaan et al., 1990; Ernst and van der Zwaan, 2004). One seemingly possible way to circumvent these problems would be to apply modern-day foraminifera depth association to palaeoassemblages. While much study has been done on modern forams, their environments and the possibility of analogous environments in the past (Gallagher et al., 2001; Hayward, 2004; Hornibrook et al., 1989; Murray, 1995), this type of direct comparison also has problems, for a few reasons. Currently, there is no consensus as to whether species are isobathyal through time (van der Zwaan et al., 1990). There is evidence that some species have migrated through time, for example the genera *Osangularia*, which migrated to the deep sea during the Cenozoic (Hornibrook et al., 1989), or the migration of *Epistominella exigua* to shallower depths at 15Ma, possibly as a response to the expansion of cooler waters to shallower depths (Kurihara and Kennett, 1992). Reconstructing life assemblages from death assemblages can also cause issues if shallow-water species have been redistributed into deeper water after death (Hornibrook et al., 1989). Lastly, marine climates are known to have fluctuated throughout the Cenozoic, and the transition to modern oceanic conditions probably did not occur until the Middle Miocene; prior to this, the well-defined break between shelf and slope may only have occurred at particular times (Douglas and Woodruff, 1981). For example, during the early Oligocene when the onset of the ACC occurred, the resulting cold water currents filled shallower parts of the ocean basins than before, allowing deep water species to move to shallower depths (Hornibrook et al., 1989).

All of the issues raised here must be taken into consideration when attempting to reconstruct palaeoenvironments and palaeobathymetry. However, after these factors have recognized, and the foraminifera data combined with sedimentary data, a general model can be created. In the least, the assemblages from the same basin can be placed in an order of increasing depths relative to one another. It was based on these principles and techniques that the palaeoenvironments for the following 7 lithofacies were determined.

Bathymetric terminology for this project follows van Morkhoven et al. (1986):
inner shelf = 0-50m, mid-shelf = 50-100m, outer shelf = 100-200m; upper bathyal = 200-600m, mid-bathyal= 600-1000m, lower bathyal = 1000-2000m; abyssal = 2000-6000m.

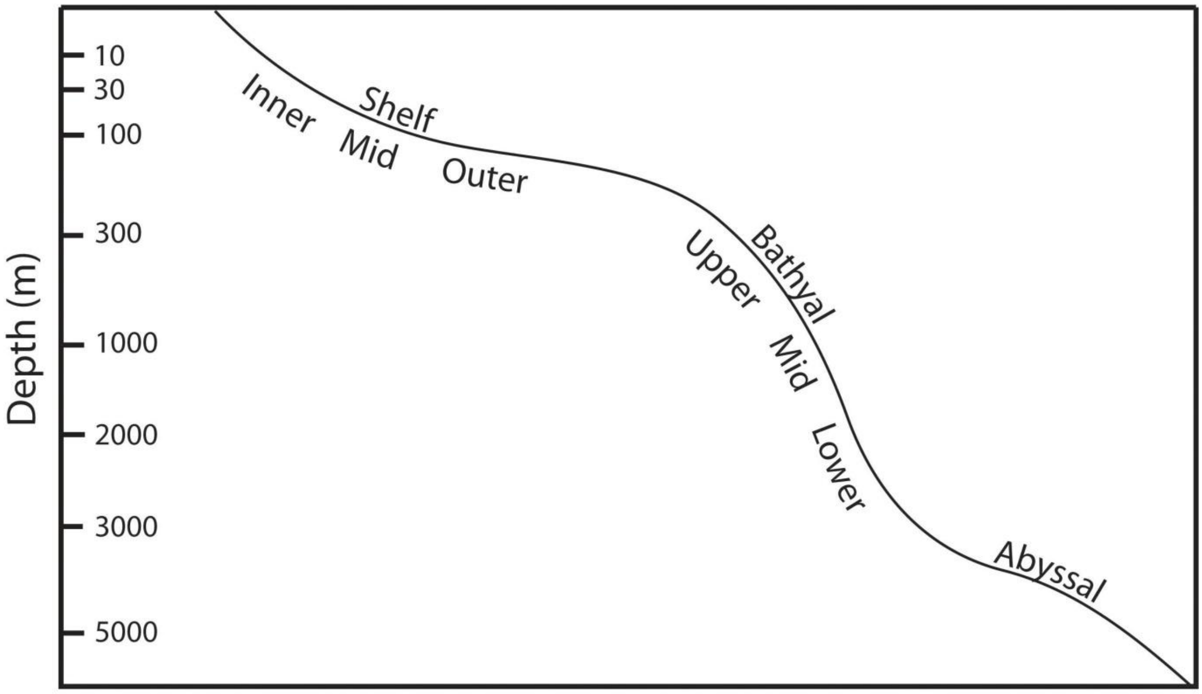


Figure 5.1 Depth boundaries for marine benthic depth zones. Modified after Hornibrook et al., (1989).

Volcaniclastic Calcareous Sandstone

This unique lithofacies combines volcanic clasts with carbonate material, making for an interesting habitat. The assemblage is dominated by two main species, *Cibicides perforatus* and *Elphidium cripsum crispum,* and includes an important environmental indicator species, *Bolivinella rugosa.* The number of species is average-high compared to other samples (S= 20), evenness is moderate (E= 0.53) and effective diversity is the second highest value of all the assemblages (H= 2.4; H_E = 10.6), 1.5x higher than the average assemblage in this study. These numbers suggest a relatively "unstressed" environment at or near equilibrium (Hammer and Harper, 2006). The extremely low percentage of planktics (2%) is indicative of a near-shore environment, an assumption supported by the presence of *Elphidium crispum crispum*, *Bolivinella rugosa*, *Notorotalia spinosa* and a non-perforate *Spirilina sp. Elphidium crispum crispum* is characteristic of sheltered oceanic embayments and the intertidal zone of inner shelf (Hayward et al., 1999); modern *Bolivinella*, and apparently those in the past, live in the inner shelf, in sandy, warm- temperate waters (Hayward, 1982); and many non-perforate species of *Spirillina*, such as *S.vivipara*, are found in calm, sheltered embayments (Yassini and Jones, 1995).

The foraminifera data alone is suggestive of a shallow, sheltered environment; the sedimentological data further refines this interpretation. The rock is a volcaniclastic sandstone, composed mainly (62%) of fine-coarse basalt grains. As discussed in Chapter 2.4, this lithofacies is characterized by large scale (5-10m) beds with sharp contacts, which most likely represent various pulses of activity from a nearby volcano. The complete lack of quartz or other detrital material in the sample is very important, as it suggests one of two scenarios: either the topography of the surrounding land was very low-lying, and therefore not conducive to much erosion, or the volcano was actually located on a broad shelf, far enough out to sea that no erosional detritus was reaching the area. This location would have been deeper than the foraminifera data suggests. As discussed in Chapter 1.2, topographic relief was low and most of the continent submerged during the Oligocene, so sedimentation rates would have been low (Cooper and Cooper, 1995). However, due to the complete lack of detritus, the more probably scenario would be the volcanic cone was located far from a sediment source, on a broad shelf. This underwater feature would have formed an ecological niche different from the surrounding environment: a sheltered, topographic high, which allowed shallow-dwelling foraminifera and other organisms to live around its edges. Water depth was probably <100m, as suggested by the presence of *Elphidium crispum crispum*, *Bolivinella rugosa* and *Notorotalia spinosa.*

Environment: Shallow (<100m), sheltered, volcanic-related topographic high

Foraminiferal wackestone

This lithofacies is defined by high planktic percentages, a benthic assemblage with high evenness and dominated by *Cibicides,* and fine, planktic foraminifera mud. The lack of sedimentary features and fossils, rare siliciclastics, fine grain size and abundance of mud is suggestive of a low energy, deep water environment. The occasional *Ophiomorpha* burrows indicated soft sediments.

The foraminifera data also supports the conclusion of a deep environment. Planktic percentages range from 69-82%, consistent with a bathyal setting. As discussed in Chapter 3.3, the evenness is high and species diversity very high when the large amount of unidentified planktics is accounted for. The higher diversity is consistent with deeper water environments, where diversity reaches a maximum in bathyal depths (ex Hayward et al., 1999; Hayward 2004). This assemblage includes an abundance of benthic species which tend to inhabit the outer shelf and upper slope, including *Lenticulina* (outer shelf-bathyal), *Planulina renzi* (bathyal), *Siphonina australias* (bathyal), *Gyroidinoides zelandicus* (mid shelf - bathyal) and *Karreriella novozealandica* (most commonly outer shelf). The combination of outer shelf and upper slope suggests a bathyal environment close to the outer shelf, in order to account for the crossover between the shelf and slope fauna.

Temperature indicator species in this assemblage are *Globoturborotalia woodi connecta* and *Catapsydrax dissimilis,* both of which indicate cool-temperate (15-18°C) surface waters

(Gallagher et al., 2001). This corresponds to previous research which shows that at this time the world was coming out of an icehouse state, and the cold-water offshoots from the ACC were no longer directly affecting the east coast of New Zealand (Fulthorpe et al., 1996).

A combination of all the discussed data indicates the depositional environment was upper bathyal, possibly close to the shelf break, at a depth range of ~300-500m. Surface water temperature was cool-temperate (15-18°C).

Environment: Upper bathyal, cool-temperate waters.

Foraminifera Packstone

This lithofacies is poorly constrained due to the lack of quality foraminifera sample obtained. The higher relative abundance of planktic foraminifera (85-90%) in this lithofacies suggests accumulation farther offshore than the previous lithofacies, an interpretation supported by the rare siliciclastic grains (0-3%) and decreased amount of carbonate mud. Statistical analysis is ineffective for the samples obtained from this lithofacies, as the percentage of unidentified foraminifera is so high that all indices become skewed. Enough specimens were identified to give a reasonable palaeogeographic reconstruction though; the benthic assemblage is similar to that of the previous, contemporaneous lithofacies, though the species diversity is much lower. Environmental indicators include *Lenticulina* (outer shelf and bathyal), *Gyroidinoides zealandica* (bathyal), and *Siphonina australis* (bathyal). Evidence for deep water, low-sedimentation rates also comes from the occasional *Zoophycos* traces observed, as well as fragments of echinoderm spines and one shark tooth.

High percentage of planktics, the presence of echinoderm spines, *Zoophycos* and bathyal-dwelling benthic foraminifera, along with the complete lack of siliciclastics, supports an interpretation of lowermost upper bathyal – mid bathyal environment. This is deeper than the contemporaneous lithofacies to the south, the foraminiferal wackestone. Water depth would be restricted from 500-1000m. Temperature indicators are restricted to the numerous

Globoturborotalia woodi connecta, which is indicative of cool-temperate surface waters (15-18°C).

Environment: Lowermost upper bathyal – mid bathyal, cool-temperate waters.

Muddy sandstone

The one site where this lithofacies is observed is a unique location. High terrigenous sediment input resulted in the formation of a sandstone, in contrast to the limestones to the east. Despite the significant difference in sediment source, foraminiferal data suggests the difference in water depth across the sites may not have been considerable, but that inland sites were receiving more terrigenous sediments than

A total of 63% of the unit is siliciclastic, up from 0-25% seen from the concurrent sites of Gore Bay to Kaikoura. Fine-grained quartz makes up 57% of the sample, in addition to minimal mica and feldspar grains. No sedimentary features or macrofossils were observed to aid in environment or depth reconstruction. The cement was completely composed of micrite.

The only locations where foraminifera were preserved was a silty horizon 16m above the base of the unit. This assemblage is dominated by infaunal specimens, mostly from the genus *Stilostomella* and *Dentalina.* A total of 15% of the fauna is infaunal, while 28% is epifaunal and 57% planktic. Due to the higher percentage of infaunals, the van der Zwaan et al. (1990) method was used on this assemblage to compare the estimated water depth to that of Gore Bay and Kaikoura. This method states the most accurate indicator of depth, when using planktic percentage, is the planktic-to-epifaunal ratio; if this is taken into consideration, and the infaunal specimens temporarily disregarded, the planktic percentage is 67%, a number not too dissimilar from the planktic percentage at Gore Bay (70%+), though lower than Kaikoura (85%+). The benthic assemblage is very similar to that seen in the Foraminifera Wackestone lithofacies, as it is dominated by *Cibicides* and includes species such as *Karreriella novozelandica, Lenticulina, Anominaloides* and *Siphonina australis.* Diversity (effective

Shannon-Wiener) is 1.3x lower in this lithofacies than the Foraminifera Packstone, although evenness, when the large group of unidentified planktics is disregarded, is higher in the muddy sandstone (0.78 vs. 0.67). The foraminifera data suggests a water depth similar to the Foraminifera Wackestone, an outer shelf- uppermost upper slope environment. The water would have been calm, with low sedimentation rates, in order to accommodate the delicate infaunal species. The key difference in this lithofacies however is the high siliciclastic input, which is not observed in the foraminifera wackestone. While the water depth may have been similar, the proximity to a sediment source was substantially different. This site suggests erosion from the content was occurring, but not in great enough quantities to have reached the eastern sites such as Gore Bay and Kaikoura. Water depth may have been between 200-500m.

Environment: Slope break, near to sediment source

Fossiliferous sandstone

A lack of foraminifera data for this lithofacies made age determination and environment reconstruction difficult. The predominant fossils, found in a fine sand matrix, were bryozoans and bivalve fragments, hosted in a quartz-rich, calcareous sandstone. These fragments may have been deposited in a shallow, high energy environment, most likely inner shelf. No other environmental indicators were present in the outcrop.

Environment: Inner-mid shelf

Impure Wackestone

A combination of increased siliciclastic input, diagenesis and high cementation rates resulted in a low percentage of foraminifera, which were impossible to extract from the host rock in most samples. As a result, very little foraminifera data is available for this lithofacies.

The sedimentology shows a substantial increase in siliciclastic input from the underlying facies at these locations. Of importance is the large fluctuations between clastic and carbonate material through these sections (ex Fig. 2.15). Near the base of the section in Gore Bay, the percentage of carbonate material is below 50%, however this is the only point in the measured section that this lithofacies contains a sandstone horizon; the rest of the section is a wackestone. A similar situation occurs at Oaro and Kaikoura, where siliciclastic material, though appearing in much higher quantities than in the lower Spyglass Formation, never accumulates in large enough quantities to constitute a sandstone. In the literature ex (Browne, 1995; Rattenbury et al., 2006), these upper Motunau Group members are referred to exclusively as sandstones, however this data shows it is apparent that, at least in the lower part of the formations, terrigenous sediment influx fluctuated substantially and rarely was enough to constitute a sandstone.

What foraminifera data is available shows very high percentages of planktics (86% at Kaikoura, 90% at Gore Bay). The few benthics are predominantly *Cibicides* and infaunals; planktics were too fragmented to identify. This data suggests bathyal depths, possibly mid slope, at a water depth of ~800-1500m.

Environment: Mid slope.

Calcareous fine sandstone

This lithofacies covers a wide range, through both space and time. While the overall character of the lithofacies is quite consistent, there exists some important local deviation. This lithofacies records numerous environmental changes, as well as possible sea level fluctuations.

This lithofacies is typified by the occurrence of fine sandstone horizons interbedded with smaller, well indurated, silty concretionary horizons. The carbonate fraction is significantly higher in the silty concretions horizon than the sandstones; composed of ~70-80% carbonate, they tend to be a wackestone, with a very low glauconite content (<1%). In contrast, the fine sandstone averages ~45% carbonate. Glauconite content is also higher, at 4% vs. <1%. The fine sandstone is very poorly indurated and highly fissile. High organic matter content was observed in some horizons at all locations.

Planktic foraminifera make up 2-6% of the fauna in this lithofacies, with the most common species being *Globigerinoides trilobus, Globorotalia mayeri mayeri, Globoturborotalia woodi,* and *G. woodi connecta*. The silty, concretion horizons have higher percentage of planktics than the sandy horizons do. One specimen of *Globigerinoides trilobus* was retrieved at Whale's Back and one specimen of *Globorotalia mayeri mayeri* at Little Lottery River. As there was only one specimen of each, no definitive conclusions can be drawn; however, these species are indicative of warm surface water (19-22°C), so their presence may be an indication of warming waters in the area.

Epifaunal benthic foraminifera assemblages were typified by *Anominaloides parvumbilia, Cibicides molestus, C. temperate, C. neoperforatus, Hoeglundia elegans, Oridorsalis umbonatus* and *Notorotalia taranaki*. Most assemblages had high dominance values and average-high diversity. Some faunas, most notably JI 44, 54 and 55, contained a higher-than-average amount of infaunal specimens, such as *Bolivinita pohana, Bolivina sp., Stilostomella sp., Uvigerina pliozea, Globocassidulina subglobosa,* and *Amphicoryna sp.* The implications of this is discuss below.

Using the method of van der Zwaan et al. (1990), whereby depth is estimated using a planktic: epifaunal ratio, these faunas were possibly located at a depth of ~40-60m, around the inner-mid shelf boundary. This estimate is supported by the percentage of planktics, as well as the foraminifera species observed: for example, *Hoeglundia elegans* is typical of the middle shelf, *Oridorsalis umbonatus* of the outer shelf, *Nonionella felmingi* of the mid-outer shelf.

One sample, JI56, contained abundant ostracods which were identified as members of the *Chytherella* and *Bisulcocythere* genera. Modern-day forms of *Bisulcocythere* are found everywhere from the mid shelf to upper slope; *Chytherella* is no more indicative of a certain water depth, as member of the genus inhabit a wide variety of environments. Two macrofossils were also identified at the site. A bivalve of the genus *Cucullaea sp.* was found essentially in life position, with both valves still attached. The other fossil was a high spired gastropod, possibly a *Maoricolpus.* As the *Cucullaea* specimen was found with no signs of transportation, it is assumed this deposit was not a result of downslope transportation. This genus is common in inner shelf environments, supporting earlier interpretations using the foraminifera assemblages.

Phosphate

At the Whale's Back location, this facies is present as an outcrop of dark coloured fine sand with highly fissile beds interbedded with well indurated concretions. There is no indication of bioturbation. The section contains a bed which is highly glauconitic (30%) and contains phosphate nodules and phosphatised brachiopods. In modern environments, phosphate nodules form in the transition zone, either between anoxic and oxygenated waters, or in situations where the water column is oxygenated but the conditions in the sediment are anoxic and highly reducing (Dam and Surlyk, 1993).Water depths range from 40-300m, and the overall sedimentation rate is low (Prothero and Schwab, 2004). Therefore, these nodules are indicative of a dysoxic, reducing environment where sedimentation rates are low and water depth is restricted to the shelf. Foraminifera data may be able to distinguish between which of the two scenarios the nodules formed in.

The foraminifera assemblage is dominated by poorly preserved *Stilostomella pomuligera* (59%). Diversity is low (H= 1.74), and the dominance high (D= 0.36) due to the large group of *S. pomuligera.* The assemblage includes other infaunal specimens including *Bolivina* *targetensis, Bulimina miolaevis, Stilostomella awamoana* and *Dentalina substrigata.* In total, the infaunal species make up 75% of the assemblage. While these numbers would typically suggest a deep environment, the planktic percentages do not, as only 5% of the sample is planktic. None of the other species (*Cibicides notocenicus, C. novozelandicus, C. targetensis* and *Anomalinoides parvumbilia*) are indicative of any particular water depth. What these foraminifera are most likely indicative of is a dysoxic environment. *Stilostomella*, along with other thin-walled, elongate, flattened species such as *Bolivina*, *Bulimina*, *Dentalina* and *Globocassidulina* are indicative of dysoxia, with oxygen contents of 0.1-0.3ml/l (Gebhardt, 1999). The epifaunal species (*Cibicides* and *Anominaloides*) are consistent with species indicative of an oxygenated water column, suggesting that of the two earlier postulated scenarios, the one consistent with the data is that the water column was oxygenated but the conditions in the sediment were anoxic and reducing (Gebhardt, 1999).

The combination of high infaunals, low planktics, high glauconite content and abundance of siliciclastics (50%) implies a shallow (~mid-shelf) environment. Together, the presence of phosphate nodules, phosphatised brachiopods, abundant *Stilostomella* and other infaunal species, fissile bedding and the absence of bioturbation are indicative of nutrient-rich dysoxia. Ocean upwelling, bringing nutrients from great depths, is a modern-day source of phosphate. A sudden influx of nutrients from deep waters results in eutrophic conditions with extremely high rates of productivity, which in turn creates an abundance of waste and remains accumulating on the shelf. Oxygen deficiency results once bacteria consuming the waste uses all the available oxygen within the sediments. This cycle of events leads to an dysoxic environment rich in phosphate and glauconite-forming material (Follmi et al., 1994; Prothero and Schwab, 2004). As plausible as this scenario is though, there is no foraminifera evidence for or against upwelling in this assemblage. The species *Globigerina bulloides* is highly indicative of upwelling regions, however it had not yet evolved by this time period. So while upwelling is a possible cause of the high phosphate and glauconite concentration, it cannot be proven by this data.

Dysoxia

In addition to the phosphogenic-related dysoxia at Whale's Back, Wandle River (JI59) and one sample location at Little Lottery River (JI55) showed signs of dysoxia within the sediment. While no one taxa is exclusively confined to a low oxygen environment, some species, when found together, are characteristic of dysoxic living conditions. Assemblages indicative of these conditions typically are made up of species of *Bolivina, Bulimina, Globobulimina, Uvigerina* and *Globocassidulina* (Smart and Murray, 1994). The tests are often small, hyaline and thin, and may have reticulation; species diversity is low (Smart and Murray, 1994). The association of multiple *Bolivina, Bulimina, Uvigerina* and *Globocassidulina* species in this assemblage, along with the low species diversity, is interpreted to indicate a low oxygen environment in shallow, sheltered waters. At Wandle River, the foraminifera assemblage, from a sample collected from a sandstone horizon (JI59), is typified by infaunal species, though the fauna is different from that observed at Whale's Back. No one infaunal species dominates the assemblage as each species contains only 1-6 specimens. The infaunals make up 26% of the assemblage, and include 4 species of *Bolivina* (*B.finlay. B.reticulata, B.subcompacta, B. zedirecta*), as well as *Bulimina pupula, Globocassidulina sp., Trifarina parva* and *Uvigerina miozea.* The epifaunal assemblage is dominated by *Cibicides temperata* (51%), *C. molestus, C. perforatus* and *Astrononion parki,* none of which are particularly indicative of a specific water depth or habitat. Only 2% of the sample is planktic, indicative of shallow waters. Dominance is high (D= 0.28) and diversity low-medium (H= 7.03), an indication of stressed environment. The fauna of Little Lottery sample JI55 contains 49% infaunal specimens which, when living together, are indicative of oxygen levels between 0.1-0.3ml/l (Smart and Murray, 1994). The fauna includes *Bolivinita* *pohana* (27%), three species of *Bolivina* (8%), as well as *Stilostomella sp.*, *Uvigerina pliozea*, *Globocassidulina subglobosa*, *Amphicoryna sp.* and a nodosariid species. The low planktic percent (2%), along with the presence of epifaunal species such as numerous *Cibicides*, suggests a shallow, sheltered environment, similar to the setting observed lower in the section at Wandle River (JI59). However, statistical analysis shows this assemblage to have the highest diversity of all the samples collected (H= 2.45). This is not consistent with faunas typical of anoxic conditions, which have low diversity and high dominance (Smart and Murray, 1994). An explanation for this inconsistency could be that the dysoxic conditions in this environment were highly a-symmetric, with anoxia sediments and an oxygenated water column above. The presence of 50% epifaunal specimens, including numerous species of *Cibicides*, as well as other indicators of oxygenated-sub oxygenated water such as *Oridorsalis umbonatus* supports this theory.

Interestingly, the deposition of the low-oxygen lithofacies at Wandle River coincides with a globally- recognized period of anoxia, defined by high abundances of bolivinids, recognized by Smart and Murray (1993). Various locations throughout the Atlantic Ocean and one in the Pacific Ocean (Kurihara and Kennett, 1992) show two large peaks (~20% and ~75% abundance) of bolivinid-dominated assemblages dated ~18.5-17Ma. The authors postulate these peaks may reflect a period of low-oxygen conditions associated with sluggish circulation of deep sea water from 20-17Ma (Smart and Murray, 1994). This sample from Wandle River is Earliest Altonian in age, approximately 18.5Ma, so it is the same age as those sites observed by Smart and Murray (1993). However, further sampling and analysis would be required to conclude if this sample's bolivinid peak is related to the global event.

In summary, this lithofacies shows record of an influx of sediments not observed in other lithofacies, an influx which is sustained over the approximately 10 million years it covers. Combined with the foraminifera data, the sedimentology also reveals small variations in water depth between the calcareous, silt concretion horizons and the fine sandstones interbedded with them. It is proposed here that the concretion horizons represent minor transgressions, higher while the less calcareous sandstone beds represent a shallowing of the water. This lithofacies also records periods of anoxic conditions, which may be related to global occurrences of the same time period which have been linked to periods of sluggish water circulation (Kurihara and Kennett, 1992; Smart and Murray, 1994).

Environment: Inner-mid shelf, eutrophic conditions leading to anoxia and phosphogenesis at some location, possibly upwelling

5.2 Palaeogeography

The environment data discussed in section 5.1 is compiled here and discussed in terms of stratigraphy. Four time frames were chosen as they best represent major snapshots in time from the late Oligocene- mid Miocene: Duntroonian, Waitakian, Otaian-Altonian and Tongaporutuan.

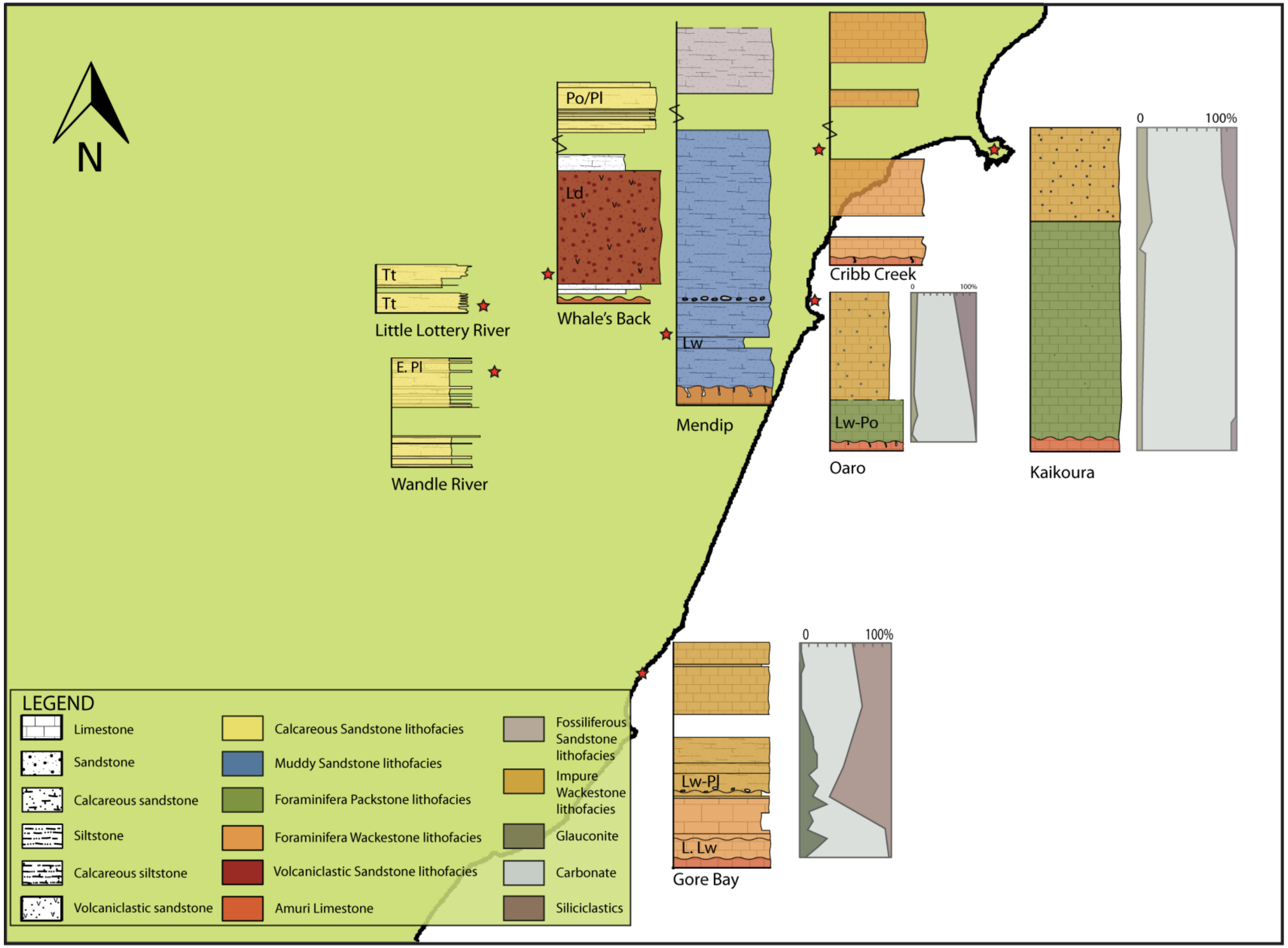


Figure 5.2 An overview summary of the ages determined at each site, as well as the fluctuations in glauconite, carbonate and siliciclastics (where available)

5.2.1 *Duntroonian, 27.3-25.2Ma*

At this time, only one location is known to have been deposited in the western part of this field area, at Whale's Back, with the Volcaniclastic Calcareous Sandstone lithofacies. Representing this time period at every other location is the Marshall Paraconformity, in place due to the non-deposition occurring as a result of cold water-offshoots from the ACC. The influx of this cold water is seen in the $\delta^{13}C$ values discussed in Chapter 4. The deposition at this time is indicative some important environmental factors. Firstly, sedimentation clearly resumed at the western sites earlier than the eastern sites; the presence of the Marshall Paraconformity at the western locations proves the currents reached that far west and did prevent deposition for some time, but that these currents retreated slowly eastwards, allowing deposition to resume at western sites up to a maximum of 2Ma earlier than eastern sites. At the time of deposition of the Volcaniclastic Calcareous Sandstone lithofacies at Whale's Back, the currents were still affecting the New Zealand continental plateau to the east.

Secondly, this location is unique because of the volcanic activity occurring. Foraminifera were deposited within a matrix of basalt and carbonate cement, suggesting a very close source of the basalt. The foraminifera species present suggest a sheltered, inner shelf environment, an interpretation not supported by the sedimentology. The most likely scenario is that the volcanic activity formed a topographic high, on which the foraminifera lived.

Water depths at this time can be inferred but there is no concrete data to confirm these interpretations. The eastern-most sites (Gore Bay-Kaikoura) were probably similar depths during the Duntroonian to those observed in the Waitakian: upper-mid slope. The western sites, including Whale's Back, Mendip, Little Lottery River and Wandle River, were at shelf depths.

In summary, the New Zealand continental plateau was still being affected by cold water currents flowing northwards during the Duntroonian, preventing deposition. By this time, the currents had retreated from the west, allowing deposition to resume at those sites. Volcanic activity was ongoing at the Whale's Back location, which appears to have created a topographic high which allowed inner-shelf dwelling fauna to reside further out to sea. There is no evidence at this time for any terrigenous siliciclastic input, which supports the theory that this environment was deeper than the foraminifera assemblage suggests, as well as confirms that there was no uplift in the terrestrial settings occurring at this time. Western sites were located at shelf depths; eastern sites at slope depths.

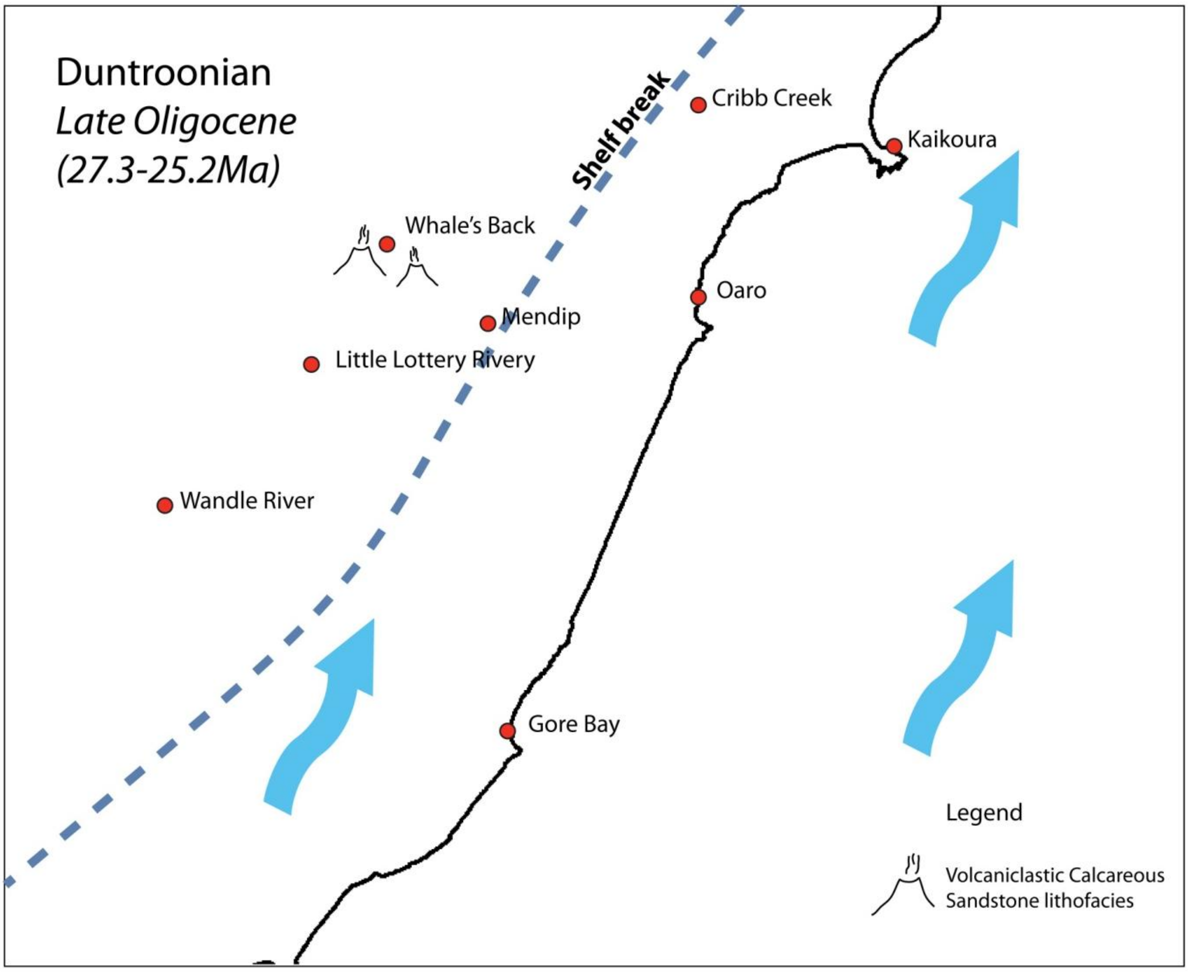


Figure 5.3 Postulated palaeogeography during the Duntroonian

5.2.2 *Early Waitakian, 25.2Ma*

The lithofacies found at this time period are the Foraminifera Wackestone, Foraminifera Packstone and Muddy Sandstone; they show evidence that the cold water currents had shifted farther east or had dissipated completely, as sedimentation had resumed at the easternmost sites (Kaikoura-Gore Bay) by the earliest Waitakian. Palaeodepths at Gore Bay and Oaro-Kaikoura are not equivalent, as demonstrated by the Foraminifera Packstones to the north and the Foraminifera Wackestones to the south; the difference in water depth may have been as much as a few hundred metres.

Although occurring at similar water depths, the Foraminifera Wackestone lithofacies does not show the sediment input that the Muddy Sandstone lithofacies does; the sandstone deposition at Mendip is the first reflection of terrigenous uplift to the west that is seen in this field area. This suggests that while uplift and associated erosion had begun by this point in time, the eastward movement of the clastic material was a slow process which did not occur immediately.

There is no evidence to suggest water depth had changed significantly from the Duntroonian to the earliest Waitakian. Kaikoura- Oaro was at mid-shelf depths, while Gore Bay- Cribb Creek was upper shelf. Mendip was most likely positioned near to the shelf break, and was located close to a new sediment source.

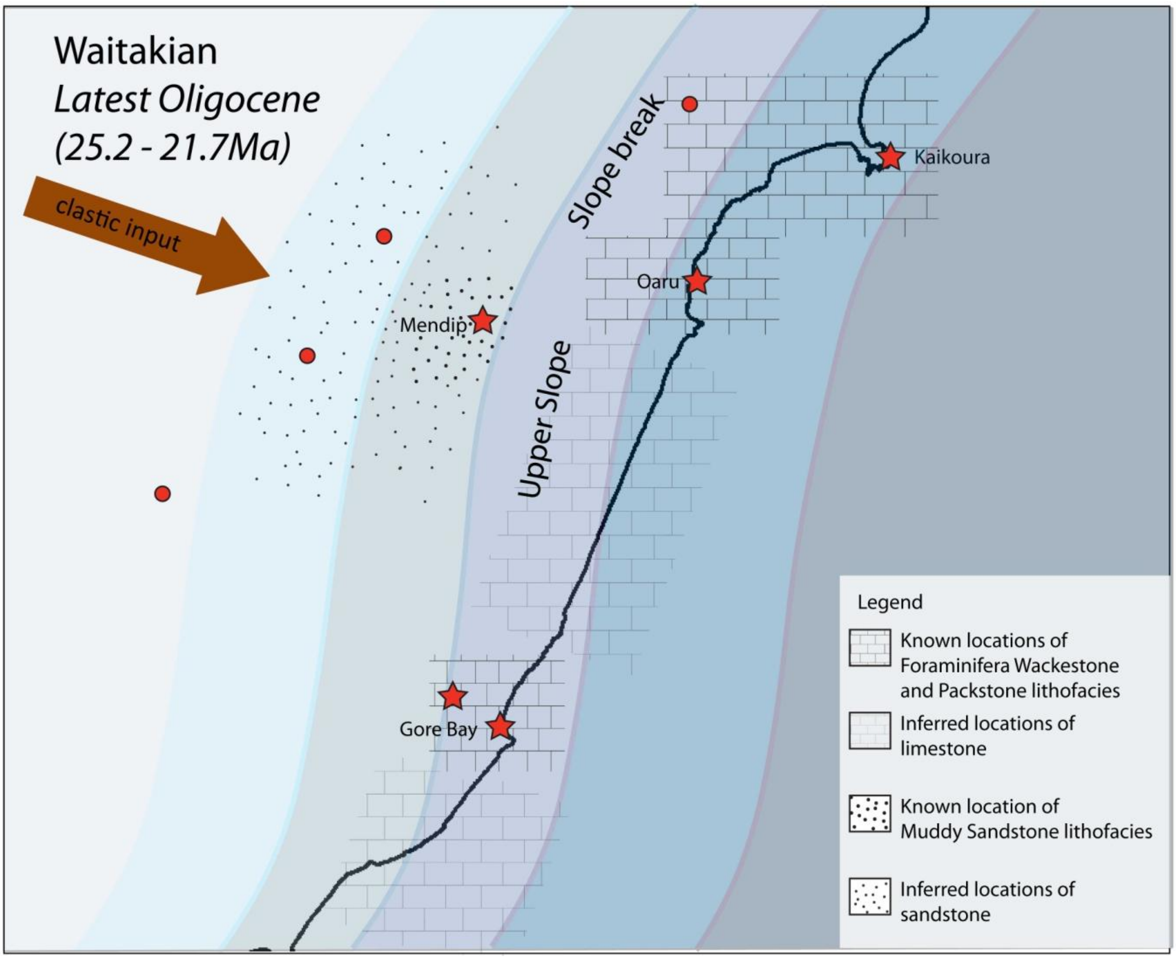


Figure 5.4 Postulated palaeogeography during the Early Waitakian

5.2.3 *Otaian-Altonian boundary – earliest Altonian, 18.7- ~18.0Ma*

By this time period, the influence of clastic sedimentation can be seen at all sites across the study area, specifically with the Impure Wackestone, Calcareous Fine Sandstone and Fossiliferous Sandstone lithofacies. All sections have a significant component of siliciclastic material, though the amount varies, especially within the sections themselves. Clearly, uplift in terrigenous settings to the west is well underway by this time.

The amount of siliciclastic material reaching the eastern sites was often not enough to form sandstones; these units became quart-rich limestones. The amount of carbonate did fluctuate greatly, most likely as the environments responded to pulses of high sediment input.

The sections at Mendip, Kaikoura and Gore Bay show indications of sea level change, though in opposite directions. A sea level rise is shown in the foraminifera and sedimentary data at the eastern sites, where the environments went from upper-mid slope to mid slope. A shallowing is observed from the data at Mendip, where the environments went from shelf break to inner-mid shelf. Clearly, the western and eastern sites had two different factors acting upon them. The shallowing observed to the west is a consequence of tectonic uplift and resulting sediment influx; the increase of sediment supply which accompanied the initiation of compression along the Alpine Fault caused the shelf to prograde eastwards, at a rate of 1.5-4.9km/Ma (Fulthorpe et al., 1996). Concurrently, the climate was warming and sea level rising (Zachos et al., 2001); this transgression is reflected at the sites further to the east, which apparently were not yet being affected by the uplift, as the environments deepened. The uplift masked the affect of sea level rise at the western locations.

Foraminifera data suggests the western locations were experiencing a period of anoxia, possibly related to the global dysoxic event which occurred from 20-17Ma and has been possibly linked to sluggish bottom water circulation. In addition, the one location at Whale's Back was also experiencing in influx of phosphate, possibly as a result of upwelling.

In summary, the compressional regime was well underway by the Otaian-Altonian boundary, reflected in the substantial increase in siliciclastic sedimentation at all study locations. The siliciclastic input was less substantial to the east, where the rock type remained a limestone despite the influx. Both sea level changes and uplift were acting up the geography at the time, with uplift and subsequent erosion resulting in a relative base level drop to the west, and sea level rise causing a deepening to the east.

The western sites show signs of experiencing anoxic conditions in the sediments, below the water column. In addition, the site at Whale's Back was high in phosphate, indicating possibly upwelling. Water depths at this time were inner-mid shelf at the western sites, and mid slope to the east (Kaikoura-Gore Bay).

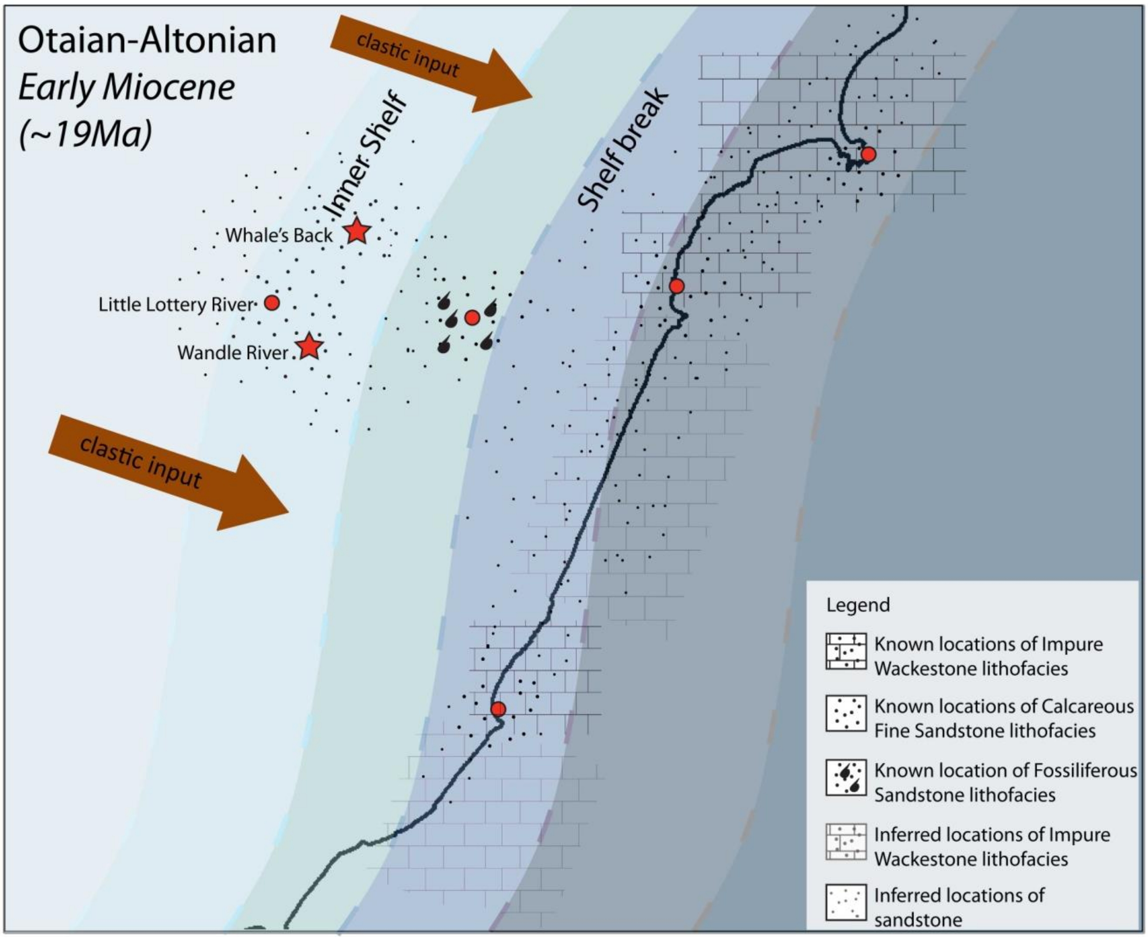


Figure 5.5 Postulated palaeogeography at the Otaian-Altonian boundary

5.2.4 *Tongaporutuan, 11.01-7.2Ma*

The final stage represented in this study area shows that the influx of siliciclastic material stayed constant through from the Otaian-Altonian boundary through to the Tongaporutuan, as the siliciclastic component from site to site through time did not vary. The only observed lithofacies recorded at this time is the upper Calcareous Find Sandstone. No data was available for water depths to the east, but to the west, it appears the sections underwent numerous small perturbations in sea level. Represented by alternating silty, concretionary horizons and sandstone beds, the changes in sea level were most likely on the order of 10's of metres, seeming to alternate between inner shelf and mid shelf. These small-scale changes could be related to a combination of small-level sea level fluctuations following the mid-Miocene climatic optimum and continued uplift.

It is hypothesised here that water depth to the east may have begun shallowing at this time, as the affects of uplift reached farther east.

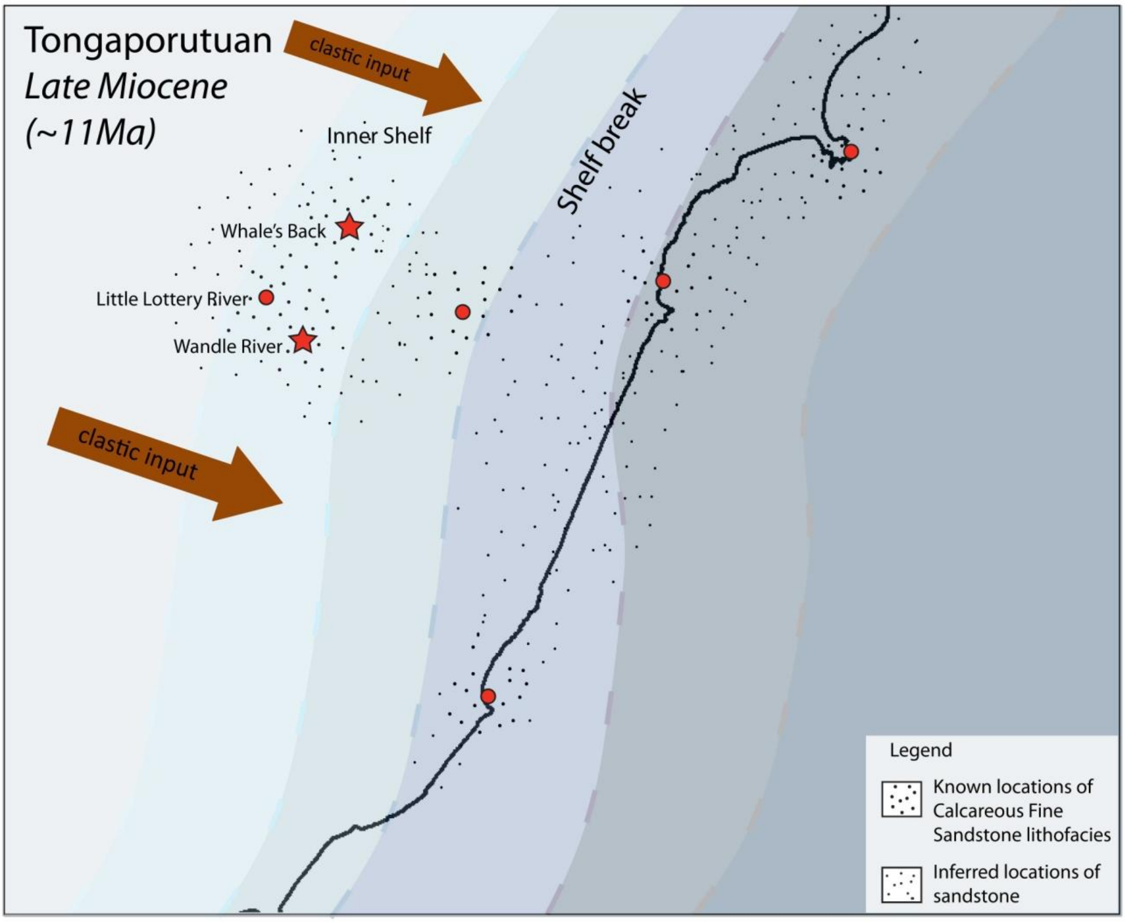


Figure 5.6 Postulated palaeogeography during the Tongaporutuan

5.3 Summary

The seven lithofacies and their associated palaeoenvironments presented in Chapter 5.1 are distributed across time, as discussed in Chapter 5.2 and shown in Figure 5.7 below. The Muddy Sandstone lithofacies records the first influx of terrigenous seen in the basin, in the

Lower Waitakian. By the Otaian- Altonian boundary, siliciclastic lithofacies, including the Fossiliferous Sandstone and Calcareous Sandstone, have replaced the earlier carbonates. Even to the east, the amount of siliciclastics has increased, though the rocks there remain carbonates (Impure Wackestone lithofacies). This influx of sediment leads to a shallowing, with the western Calcareous Sandstone lithofacies being deposited along the inner-mid shelf. Initially, this shallowing is not observed to the east; the eastern localities where the Impure Wackestone is located was experiencing a deepening due to global sea level rise, coinciding with depleted global $\delta^{18}O$ values (see Fig 5.7). This sea level rise masked the effects of uplift to the west for a period of time before the siliciclastic input supersedes the sea level rise as the more prominent force acting upon the New Zealand palaeogeography.

This sedimentary history strongly resembles that of North-Central Marlborough, which is also closely linked to the evolving convergent plate margin (Browne, 1995). The Marshall Paraconformity is seen in Marlborough and is thought to have developed at a similar time to that in this study area, though the surface in Marlborough covers a greater time period (Browne, 1995). Deposition following the Paraconformity resumed at bathyal settings, the same depth as pre-Paraconformity sedimentation, in contrast to the slight shallowing observed from the Amuri to the overlying facies in this project. Carbonate sedimentation continued through the Waitakian, with no correlative to the southern Muddy Sandstone facies; a change to terrigenous siliciclastic sedimentation occurs in the latest Waitakian, at the same time the change is observed in the Impure Wackestone. Depositional settings ranged from fluvio-lacustrine to alluvial fan and deeper to shelf-bathyal in the Marlborough area (Browne, 1995). It can be concluded that the tectonic influences on the north Canterbury Basin also extended to the Marlborough area to the north.

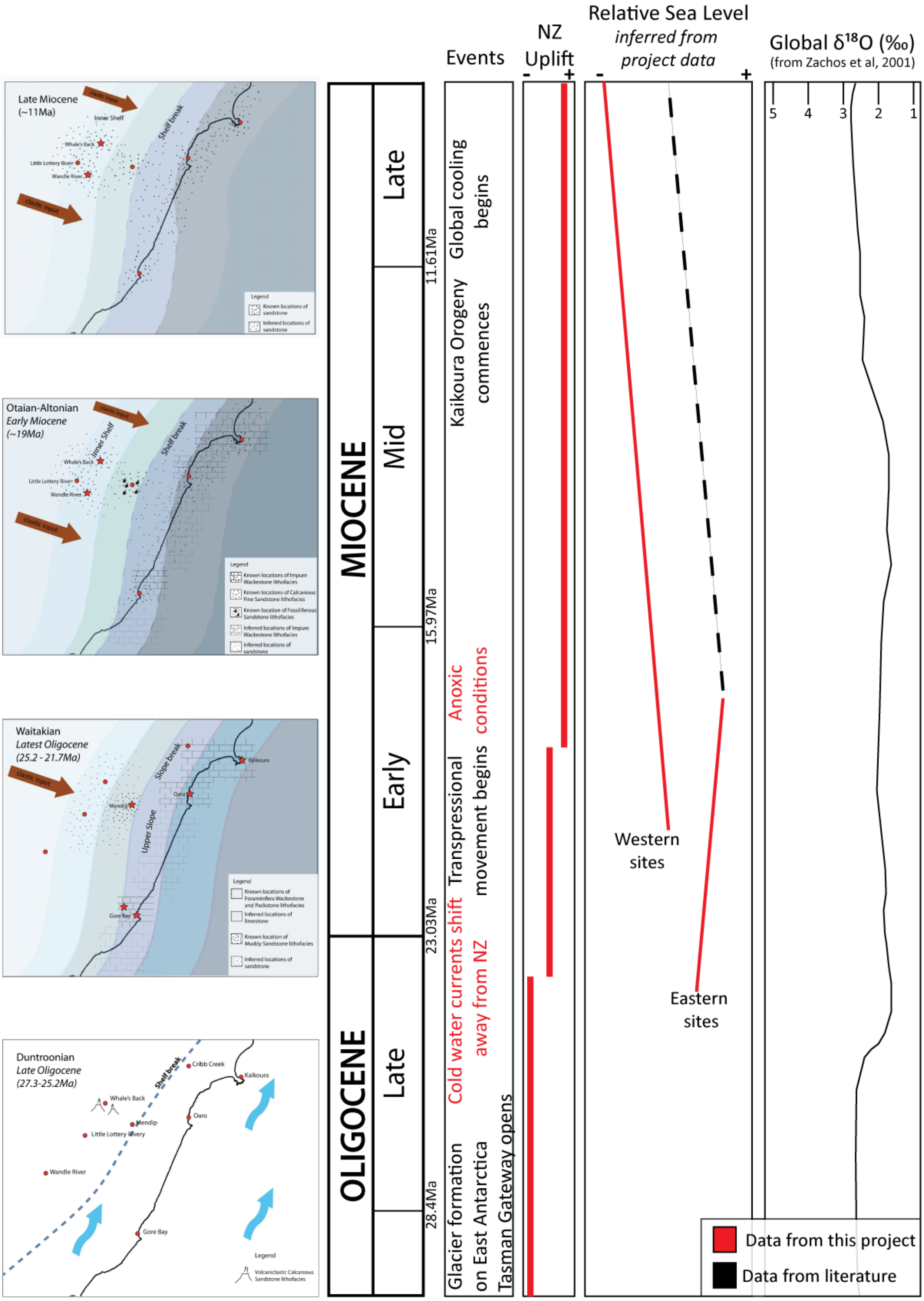


Figure 5.7 Compilation of all data presented in this project, including palaeoenvironments, uplift and relative sea level changes, combined with known $\delta^{18}O$ data as well as global and local events. Uplift (-) represents no uplift activity, while Uplift (+) represents uplift activity in the west. Relative sea level differences are represented as shallowing waters/regressions (-) or deepening/transgressions (+).

6. CONCLUSION

The following conclusions can be drawn from the data presented:

1. A possible topographic high, formed by a volcanic cone, was present during the Duntroonian at Whale's Back. This topographic high provided a unique habitat for foraminifera and other biota living in the area, as the water in the vicinity of the volcanic cone was deeper than the environment provided by the cone.
2. The onset of uplift to the west is recorded by an influx of terrigenous sediments in the earliest Waitakian. Terrigenous sediments did not reach farther east until later, as they do not appear in the rocks at Gore Bay and Kaikoura until Late Waitakian.
3. Dysoxic condition may have been present in the western sites during the early Altonian, coincident with the global anoxic event recognized by Smart and Murray (1994). These periods in time are marked by a sharp increase in the number of bolivinids and other infaunal species in an assemblage, to 25-75%.
4. During the Altonian, the effects of sea level rise and uplift can be recognized in both the sedimentary and foraminifera data, and they appear to have been working in opposite directions. Uplift and subsequent erosion resulted in a shallowing to the west, while sea level rise due to a warming climate resulted in deepening of environments to the east. The effects of sea level rise were masked in the west by the uplift.

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Appendix A

Thin section data, from point counting and visual estimation.

	Sample info	Carbonates%	Siliciclastics%	Glauc%	Dunham	Cement type
Sample	Location	Carbonates%	Siliciclastics%	Glauc%	Dunham	Cement type
1	Gore Bay	95	0	5	Wackestone	Micrite
4	Gore Bay	30	62	8	Dolomitic fine sandstone	spar, dolomite
5	Oaru	90	0	10	Wackestone	micrite (75%) spar (25%)
8	Oaru	85	5	10	Packstone	micrite (80%) and spar (20%)
10	Spyglass glauc bed	65	2	30	Packstone	Micrite (95%) and spar (5%)
11	Spyglass Limestone	94	1	5	Wackestone	Micrite
12	Spyglass Limestone	94	1	5	Wackestone	Micrite
13	Spyglass Limestone	90	1	9	Packstone	Micrite
14	Spyglass Limestone	95	1	4	Packstone	micrite (40%) spar (60%)
16	Waima Fm	75	15	10	qtz-rich wackestone	Micrite and spar
23	Mendip Mt Brown	45.0	51.0	4	Sandstone	Spar
24	Mendip SS	32.0	63.0	5	calcareous muddy sandstone	Micrite
28	Gore Bay Quarry	82.0	7.0	11	Wackestone	Micrite
29	Upper Gore Bay	55	43	2	qtz-rich wackestone	micrite (66%) and spar (33%)
34	Cribb Creek	75	22	3	Wackestone	micrite (5%) and spar (95%)
45	Whale's Back Mioc	50	43	7	calcareous fine sandstone	Spar
49	Whale's Back Volc	34	61	5	volcaniclastic calcareous SS	Spar
52	Little Lottery River	85	15	0	Siltstone	Spar
54	Little Lottery River	48	48	4	calcareous fine sandstone	Spar
58	Wandle River	53	50	3	calcareous fine sandstone	Spar
CC+9	Cribb Creek	88	10	2	Wackestone	Micrite
CC+20	Cribb Creek	72	25	3	Wackestone	Micrite
CC+30	Cribb Creek	65	20	15	Wackestone	Micrite
	Pointcounter used					

	Total clast composition									
Sample	**Bioclasts**	**Carbonates**	**noncarbonates**	*quartz*	*glauc*	*feldspars*	*calcite*	*mica*	*other*	**total %**
1	5	90	5	*5*						100
4	2	28	70	*49*	*8*	*4*		*1*	*8*	100
5	30	60	10	*0*	*10*	*0*		*0*		100
8	30	55	15	*3*	*10*	*0*	*2*	*0*		100
10	40	25	35	*2*	*30*			*3*		100
11	55	39	6	*1*	*5*					100
12	65	29	6	*1*	*5*					100
13	50	40	10	*1*	*9*					100
14	45	50	5		*4*			*1*		100
16		75	25	*13*	*10*		*2*			100
23	1.4	43.3	55.3	*45.7*	*4.2*				*5.4*	100
24	0	31.8	68.2	*56.6*	*5.2*	*1*		*2.6*	*2.9*	100
28	36	46	18	*7*	*11*					100
29	10	45	45	*33*	*2*	*0.5*	*0.5*	*1*	*9*	100
34	11	63.9	25.1	*20.5*	*3.2*	*1*		*0.2*	*0.2*	100
45	1.2	48.9	49.9	*42.5*	*5.5*			*1.26*		100
49	3	31	66						*66.6*	100
52	1	84	15		*<1*					100
54	0	48.3	51.7	*46.2*	*4.2*	*0.5*			*0.7*	100
58	0.5	46.5	53	*47*	*2.7*	*2.5*		*0.2*		100
CC+9	0	88	12		*2*					100
CC+20	0	72	28		*3*					100
CC+30	0	65	35		*15*					100

	Bioclast breakdown (normalized)								Foram breakdown	
Sample	**Bryoz**	**Forams**	**Bivalve**	**Gastrop**	**Echin**	**ostracod**	**Fragments**	**total%**	**Benthic**	**Planktic**
1		100						100		
4		100					0	100		
5		25					75	100	33	67
8		30			3	1	66	100	5	95
10		50			1		49	100	2	98
11		50					50	100	10	90
12		35			1		64	100	3	97
13		70					30	100	0	100
14		90					10	100	5	95
16		100						100	0	100
23							100	100		
24								0		
28	1	98			1			100		
29								0	5.8	94.2
34		54.5					45.5	100	8.3	91.7
45		100						100		
49	2	70	20	3	5			100		
52		100						100		
54								0		
58		100						100		
CC+9								0		
CC+20								0		
CC+30								0		

Appendix B

A list of all the foraminifera collected at each sample site and their abundance.

	SAMPLE JI1	
Textulariida	*agglutinated sp.*	1
	Dorthia minima	1
	Textualarid sp.	1
	Vulvulina pennatula	1
Lagenida	*Lenticulina gyroscalpra*	1
	Lenticulina pusilla	2
	Lenticulina sp.	1
	Planulina renzi	1
Miliolida		0
Rotaliida	*Anomalinoides orbiculus*	2
	Cibicides notocenicus	1
	Cibicides novozelandicus	7
	Cibicides sp.	1
	Cibicides temperata	6
	Gavelinella zealandica	1
	Notorotalia sp.	1
Buliminida	*Rectuvigerininae rerensis*	2
Lituolida	*Bolivinopsis cubensis*	1
Planktics	*Globigerina euapertura*	2
	Globoturborotalia woodi connecta	11
	Globorotalia mayeri pseudocontinuosa	4
	Globorotalia mayeri semiverva	3
	Unknown planktics	49
Total		**100**

	SAMPLE JI2	
Textularids	*Karreriella novozealandica*	2
	Siphotextularia awamoana	1
Lagenids	*Amphicoryna hirsuta*	1
	Laevidentalina filiformis	1
	Lenticulina pusilla	1
	Planularia halophora	3
Miliolids		0
Rotalids	*Cibicides notocenicus*	3
	Cibicides novozelandicus	2
	Cibicides temperata	3
	Cibicides sp.	4
	Gyroidinoides zelandicus	1
	Siphonina australias	2
Buliminida	*Bolivina pontis-anastomosa intermediate*	1
	Bolivina sp.	2
Lituolida		0
Planktics	*Globigerina c. ciperoensis*	1
	Globigerina euapertura	14
	Globigerina labiacrassata	2
	Globoturborotalia woodi connecta	4
	Globoquadrina dehiscens	2
	Globoquadrina tripartita	2
	Globorotalia mayeri psedocontinuosa	1
	Unknown benthics	2
	Unknown planktics	45
Total		**100**

	SAMPLE JI4	
Textulariida		0
Lagenida	*Chrysalogonium verticale*	1
	Laevidentalina filiformis	3
Miliolida		0
Rotaliida	*Cibicides perforatus*	2
	Cibicides temperata	2
	Nonionella novozealandica	1
Buliminida		0
Lituolida		0
Planktics		-
	Unknown benthics	1
	Unknown planktics	90
Total		**100**

	SAMPLE JI6	
Textulariida		0
Lagenida		0
Miliolida		0
Rotaliida	*Anomalinoides parvumbilia*	1
	Cibicides novozelandicus	1
	Cibicides temperata	3
	Gyroidinoides zelandicus	1
	Notorotalia sp.	1
Buliminida	*Rectobolivina maoriella*	1
	Stilostomella pomuligera	1
Lituolida		0
Planktics	*Globoturborotalia woodi connecta*	3
Reworked	*Nuttalides carinotruempyi*	1
	Unknown planktics	87
Total		**100**

	SAMPLE JI15	
Benthics	*Lenticulina* and *Cibicides*	14
Planktics	*Globigeroides*	86
Total		**100**

	SAMPLE JI8	
Textulariida	*Haeuslerella hectori*	1
Lagenida	*Chrysalogonium verticale*	1
	Lenticulina gyroscalpra	1
Miliolida		0
Rotaliida	*Anominaloides sp.*	2
	Cibicides novozelandicus	2
	Cibicides perforatus	2
	Cibicides sp.	2
	Cibicides temperata	7
	Siphonina australis	1
Buliminida	*Rectouvigerina rerensis*	1
Lituolida	*Cyclammina incisa*	2
Planktics	*Globoturborotalia woodi ?*	7
	G. woodi connecta	1
	Unknown benthics	12
	Unknown planktics	58
Total		**100**

	SAMPLE JI25	
Textulariida	*Karreriella novozelandica*	2
	Textularia pseudomiozea	1
Lagenida	*Chrysalogonium verticale*	1
	Lagenonodosaria hirsuta	1
	Lenticulina pusilla	1
Miliolida		0
Rotaliida	*Anomalinoides parvumbilius*	3
	Cibicides notocenicus	2
	Cibicides novozelandicus	1
	Cibicides sp.	7
	Cibicides temperata	6
	Gyroidinoides zelandicus	3
	Siphonina australis	5
Buliminida	*Stilostomella verneuilii*	1
	Bolivina subcompacta	1
	Stilostomella sp.	1
Lituolida	*Dentalina soluta*	3
	Dentalina substrigata	4
Planktics		-
	Unknown planktics	57
Total		**100**

	SAMPLE JI28	
Textulariida	*Karriella novozelandica*	1
Lagenida	*Chrysalogonium verticale*	4
	Lenticulina psuedocalcorata	1
Miliolida		0
Rotaliida	*Cibicides cf. novozelandicus*	1
	Cibicides notocenicus	1
	Cibicides novozelandicus	2
	Cibicides temperata	5
	Siphonina australis	2
Buliminida	*Stilostomella fijiensis*	1
Lituolida		0
Planktics	*Catapsydrax dissimilis*	2
	Globoturborotalia woodi conne	4
	Globorotalia mayeri semivera	2
	Unknown planktics	74
Total		**100**

	SAMPLE JI44	
Textulariida	*Bigenera sp.*	1
	Textularia miozea	3
Lagenida	*Dentalina substrigata*	1
	Lenticulina sp.	2
Miliolida		0
Rotaliida	*Anomalinoides parvumbilius*	1
	Cibicides notocenicus	2
	Cibicides novozelandicus	2
	Cibicides temperata	6
	Cibicides sp.	3
Buliminida	*Bolivina targetensis*	4
	Bulimina miolaevis	2
	Stilostomella awamoana	6
	Stilostomella pomuligera	59
	Trifarina parva	1
Lituolida	*Ammobaculites calcareus*	2
Planktics	*Globoturborotalia woodi conn*	4
	Globigerinoides trilobus	1
	Unknown planktics	
Total		**100**

	SAMPLE JI49	
Textulariida		0
Lagenida		0
Miliolida		0
Rotaliida	*Anominaloides fasciatus*	2
	Cibicides notocenicus	8
	Cibicides perforatus	32
	Cibicides temperata	2
	Cibicides vortex	3
	Cibicides sp.	1
	Elphidium crispum crispum	16
	Eoeponidella zealandica	4
	Heronallenia wilsoni	3
	Notorotalia spinosa	9
Buliminida	*Bolivinella rugosa*	2
	Buliminoides sp.	2
Robertinida	*Epistominella sp.*	3
	Hoeglundina sp.	1
Lituolida		0
Spirilinida	*Spirillina sp.*	1
Planktics	*Globorotaloides testarugosus*	1
Reworked	*Gaudryina proreussi*	2
	Globigerina linaperta	1
	Unknown benthics	6
	Unknown planktics	1
Total		**100**

	SAMPLE JI54	
Textulariida		0
Lagenida		0
Miliolida	*Spiroloculina henbesti?*	1
Rotaliida	*Anomalinoides parvumbilia*	1
	Cibicides molestus	2
	Cibicides neoperforatus	7
Buliminida	*Bolivinita pohana*	2
	Stilstomella pomuligera	1
Lituolida		0
Robertinida	*Hoeglundia elegans*	2
Planktics	*Globorotalia mayeri mayeri*	1
	Unknown benthic	2
	Unknown planktic	1
Total		**20**

	SAMPLE JI52	
Textulariida		0
Lagenida		0
Miliolida	*Quinqueloculina sp*	1
Rotaliida	*Anomalinoides parvumbilia*	11
	Cibicides molestus	12
	Cibicides neoperforatus	2
	Cibicides temperata	2
	Cibicides sp.	2
	Nonionella flemingi?	1
	Oridorsalis umbonatus	11
	Pullenia buliminoides	1
Buliminida	*Bolivinita pohana*	20
	Rectobolivina parvula	1
	Uvigerina pliozea	2
Lituolida		
Robertinida	*Hoeglundia elegans*	9
Planktics	*Globorotalid sp.*	6
	Unknown benthics	19
Total		**100**

	SAMPLE JI55	
Textulariida	*Textularia miozea*	2
Lagenida	*Amphicoryna hirsuta f. sublineata*	6
	Nodosarid	1
Miliolida		0
Rotaliida	*Anomalinoides parvumbilia*	22
	Cibicides molestus	6
	Cibicides neoperforatus	2
	Cibicides novozelandicus	1
	Cibicides vortex	1
	Gavelinopsis sp.	1
	Notorotalia taranaki	8
	Oridorsalis umbonatus	3
Buliminida	*Bolivina albatrossi*	3
	Bolivina cf. barnwelli	3
	Bolivina cf. subcompacta	2
	Bolvinita pohana	27
	Stilstomella pomuligera	3
	Uvigerina pliozea	2
Lituolida	*Globocassidulina subglobosa*	2
Robertinida	*Hoegludina elegans*	2
Planktics	*Globoturborotalia woodi connecta?*	2
	Unknown benthics	1
Total		**100**

	SAMPLE JI59	
Textulariida		0
Lagenida	*Planulina sp.*	1
Miliolida		0
Rotaliida	*Astrononion parki*	6
	Cibicides molestus	5
	Cibicides perforatus	6
	Cibicides temperata	51
	Elphidium advenum	1
	Nonionella novozealandica	2
Buliminida	*Bolivina finlay*	2
	Bolivina reticulata	2
	Bolivina subcompacta	2
	Bolivina zedirecta	6
	Bulimina pupula	1
	Globocassidulina sp.	5
	Trifarina parva	4
	Uvigerina miozea	4
Lituolida		0
Planktics	*Globoturborotalia woodi*	1
	Globoturborotalia woodi connecta	1
Total		**100**

Data from PAST statistics program

SAMPLE	JI1	JI2	JI4	JI6	JI8	JI25	JI28
Taxa_S	22	23	7	10	15	18	13
Individuals	100	100	100	100	100	100	100
Dominance_D	0.266	0.232	0.812	0.7594	0.3632	0.3418	0.5554
Simpson_1-D	0.734	0.768	0.188	0.2406	0.6368	0.6582	0.4446
Shannon_H	2.047	2.202	0.4947	0.6539	1.61	1.794	1.173
Evenness_e^H/S	0.352	0.3932	0.2343	0.1923	0.3336	0.3342	0.2487
Effective H (e^H)	7.74	7.74	1.64	1.92	5.00	6.01	3.23
SAMPLE	JI44	JI49	JI52	JI55	JI54	JI59	
Taxa_S	17	20	15	22	11	17	
Individuals	100	100	100	100	20	100	
Dominance_D	0.3628	0.153	0.1284	0.1408	0.17	0.2812	
Simpson_1-D	0.6372	0.847	0.8716	0.8592	0.83	0.7188	
Shannon_H	1.738	2.357	2.26	2.452	2.107	1.95	
Evenness_e^H/S	0.3346	0.5281	0.639	0.5278	0.7474	0.4135	
Effective H (e^H)	5.69	10.56	9.58	11.61	8.22	7.03	

Appendix C

Raw geochemistry data, values of $\delta^{13}C$ and $\delta^{18}O$.

Sample	Height(m)	Section	d13C (VPDB)	d18O (VPDB)
CRIBB CREEK				
CC-5	-5	CC	2.14	-1.65
CC-4	-4	CC	1.67	-1.73
CC-3	-3	CC	1.96	-1.89
CC-2	-2	CC	2.12	-1.37
CC-1	-1	CC	1.83	-1.05
CC0	0	CC	1.24	-2.83
CC+1	1	CC	1.14	-2.23
CC+2	2	CC	1.01	-1.87
CC+3	3	CC	0.70	-2.98
CC+4	4	CC	0.85	-1.93
CC+5	5	CC	1.05	-2.28
CC+9	9	CC	0.78	-1.74
CC+17	17	CC	0.88	-2.01
CC+20	20	CC	0.09	-3.35
CC+30	30	CC	0.21	-2.13
GORE BAY				
GB-5	-3	GB	1.35	-0.87
GB-4	-2	GB	1.41	-1.01
GB-3	-1	GB	1.50	-1.18
GB-2	0	GB	1.41	-1.36
GB-1	1	GB	1.49	-0.85
GB0	2	GB	1.53	-0.56
GB+1	3	GB	0.88	-0.28
GB+2	4	GB	0.81	-0.68
GB+3	5	GB	1.00	-0.46
GB+4	6	GB	0.74	-0.25
GB+5	7	GB	0.28	0.18
GB+6	8	GB	-0.10	-0.33
GB+7	9	GB	0.00	-0.75
GB+9	10	GB	-1.12	0.47
GB+10	11	GB	-0.65	-0.17
GB+15	15	GB	-1.93	-0.55
GB+20	20	GB	0.62	-0.91
GB+30	30	GB	-1.04	-0.44
GB+40	40	GB	-1.35	-0.85

KAIKOURA				
KSB-5	-5	KSB	2.55	-0.20
KSB-4	-4	KSB	2.07	-1.17
KSB-3	-3	KSB	2.13	-1.10
KSB-2	-2	KSB	2.02	-0.89
KSB-1	-1	KSB	2.07	-0.54
KSB0	0	KSB	0.73	-0.68
KSB+1	1	KSB	0.76	-0.65
KSB+2	2	KSB	0.97	-0.57
KSB+3	3	KSB	0.87	-0.34
KSB+4	4	KSB	1.12	-0.40
KSB+5	5	KSB	0.51	-0.55
KSB+6	6	KSB	0.98	0.05
KSB+7	7	KSB	0.37	-0.69
KSB+8	8	KSB	-1.06	-0.49
KSB+9	9	KSB	-1.01	-1.54
KSB+10	10	KSB	0.75	-0.47
KSB+15	15	KSB	0.29	-0.63
KSB+20	20	KSB	1.01	-0.05
KSB30	30	KSB	0.96	-1.02
KSB+40	40	KSB	0.71	-1.12